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Solar Thermal Power Systems
Advanced Solar Thermal Technology Project

DOE/JPL-1060-30, Rev. 1
Distribution Category UC-62

Electrochemical Energy Storage Systems for Solar Thermal Applications

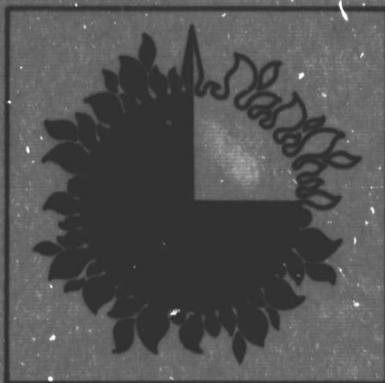
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by
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

(JPL PUBLICATION 79-95, REVISION 1)



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S. Krauthamer
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ABSTRACT

This report evaluates existing and advanced electrochemical storage and inversion/conversion systems that may be used with terrestrial solar-thermal power systems. It assesses the status, cost and performance of existing storage systems, and projects the cost, performance, and availability of advanced systems. A prime consideration is the cost of delivered energy from plants utilizing electrochemical storage.

The report addresses three broad areas: (1) the electrochemical, or battery, component of the storage system; (2) the balance of system, or all components other than the battery; and (3) the overall solar-thermal plant with electrochemical storage. Included in the latter area is a tabulation of the levelized costs of delivered energy from complete plants with sixteen different, advanced electrochemical systems. This tabulation ranks the systems in order of economic attractiveness.

The results of the study indicate that the five most attractive electrochemical storage systems are the: iron-chromium redox (NASA LeRC), zinc-bromine (Exxon), sodium-sulfur (Ford), sodium-sulfur (Dow), and zinc-chlorine (EDA).

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EXECUTIVE SUMMARY

This report summarizes the results of an investigation initiated at the request of the JPL Solar Thermal Power Systems Project Office. The purpose of this investigation was to evaluate existing and advanced electrochemical storage and inversion/conversion systems that may be used with future terrestrial solar-thermal energy conversion systems. Specific objectives were to assess the status and performance of existing systems, establish current cost (for mid-1979 time frame) and to project cost, performance, and availability of advanced systems. The results may be used to evaluate the impact of electrochemical storage systems upon near- and far-term solar thermal plants.

The investigation adopted a three-step approach. First, a review was made of the existing literature on electrochemical storage and inversion/conversion systems. Second, discussions were held with the manufacturers and developers of these systems to obtain an update on the status of these systems. Third, the information collected was reduced, tabulated, and analyzed in this report.

Three categories of information were obtained. The first deals with the electrochemical or battery portion of the storage system. The second encompasses the balance of system (BOS), which includes all components of the storage systems except the battery. The third category treats the solar thermal plant in its entirety, with electrochemical storage. Included in the latter category is a tabulation of levelized costs of delivered energy from an advanced design parabolic dish power plant with sixteen different, advanced electrochemical systems. This tabulation ranks the systems in order of economic attractiveness.

A. RESULTS: BATTERY STUDY

This section summarizes the findings of the battery portion of the investigation.

- The existing lead-acid battery is the only electrochemical system presently considered technically ready for use in near-term demonstration programs. The specific type of lead-acid battery suitable for solar thermal applications is one that is designed for repetitive, deep discharges (of 5- to 8-hour duration on a daily basis) at moderate to high power densities. All of these characteristics are present in the "motive power" or "traction" type lead-acid battery. Depending on the given duty cycle, this type of lead-acid battery will cost from \$170 to \$220/kWh, deliver 2000 cycles at 80% depth of discharge, and operate with an energy efficiency of 70% to 85%. There are four large and several smaller manufacturers of this type of cell. The major manufacturers are C&D, ESB, Gould, and Globe Union. These companies are capable of producing

sufficient quantities of batteries for megawatt-size demonstration plants; one reports an annual surplus production capacity of 50 to 80 MWeh, while another has a 50 MWeh per year surplus.

Several battery manufacturers are in the process of developing advanced lead-acid batteries for utility and electric vehicle applications. These advanced lead-acid batteries are expected to perform better, have lower maintenance requirements and cost less than existing lead-acid batteries as shown below.

- Table 1 presents a summary of the most important findings on sixteen advanced battery systems. The information may be used to estimate initial cost, performance, and availability of these systems. The highlights of Table 1 are presented in the following brief descriptions of each column.

BATTERY TYPE: This identifies the electrochemical systems and their developers. All sixteen systems in this column are considered potential candidates for solar thermal applications.

INITIAL COST: This gives the projected initial capital cost in terms of \$/kWeh for storage systems with conventional configurations (internal storage of reactants), and \$/kWe + \$/kWeh for systems with unconventional configurations (external storage of reactants). In the latter case, the \$/kWe is associated with the cell stack (or electrochemical converter) and the \$/kWeh is associated with the external tank with reactants. The costs for systems with conventional configurations range from about \$32 to \$132/kWeh (1979 dollars), where costs are normalized to the energy delivered by a fully charged battery when discharged to 80% of capacity.

NUMBER OF CYCLES: This gives the projected cycle life of the systems in terms of number of cycles at 80% depth of discharge (DOD) except the nickel-zinc system, which is at 40% DOD. Projected cycle lives range from about 1000 to 10,000 cycles.

BATTERY EFFICIENCY: This gives the projected energy efficiency for each of the systems at an 80% depth of discharge. This "round-trip" efficiency is the ratio of energy output during the discharge portion of a cycle to energy input during the charge portion of a cycle times 100%. The projected efficiencies range from about 50% to 90%.

THROUGHPUT EFFICIENCY: This is the product of battery efficiency and inverter/converter efficiency neglecting

Table 1. Cost and Performance of Advanced Electrochemical Storage Batteries

Battery Type	Initial Cost ¹	# Cycles At 80% DOD	Battery Efficiency	Throughput Efficiency ⁴	Projected Availability	Probability of Availability ²
Adv. Pb-Acid	\$116-\$130/kWh	4000	80-85%	73-78%	1985	0.95
Na-S (GE)	\$43/kWh	2500	76%	70%	1985	0.95
Na-S (FORD)	\$43/kWh	2500-5000	75%	69%	1985	0.80
Na-S (DOW)	\$33/kWh	3000	90%	83%	1990	0.20
Fe-Cr Redox (LeRC)	\$132/kWh + \$22/kWh	10000	75%	69%	1990	0.80
Zn-Cl ₂ (EDA)	\$59/kWh + \$27/kWh	2500-3500	71-74%	65-68%	1985	0.95
LiM-FeS (Argonne)	\$54/kWh	3000	85%	76%	1990	0.70
Zn-Br ₂ (Gould)	\$49-\$59/kWh	2500	70%	65%	1990	0.70
Zn-Br ₂ (Exxon)	\$32/kWh	2500-5000	80%	74%	1990	0.70
Zn-Br ₂ (GE)	\$58/kWh	2000	75%	69%	--	--
Fe-Air (Westg)	\$32/kWh	1000	50%	46%	1985	0.60
Ni-Fe (Westg)	\$54/kWh	2000	60%	55%	1985	0.70
Ni-Fe (EP)	\$65/kWh	2000	65-70%	60-65%	1990	0.70
Ni-H ₂ (ERC)	\$65/kWh	10000	60-70%	55-65%	1990	0.20
Ni-Zn (Gould)	\$108/kWh	2000 ³	90%	83%	1985	0.60
H ₂ -Cl ₂ (BNL)	\$81/kWh	--	65%	60%	--	--

¹Updated to mid-1979 dollars, costs are based on 80% DOD and are for battery only (not balance of systems), also batteries are overdesigned so that they will deliver full rated capacity at end of indicated number of cycles

²Predicated upon EPRI data, vendor data, and best engineering judgement

³40% DOD

⁴Throughput efficiency (product of battery and inverter/converter efficiencies) - see Appendix B

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all losses due to cables, connections, breakers, fuses, etc. Values are noted to range from 55% to 78%.

PROJECTED AVAILABILITY: This gives the projected availability date for each system. This is the time when the developers anticipate that they will be able to produce large numbers of their systems (on the order of 1000 MWeh worth of batteries per year). Projected availability dates are in the 1985 to 1990 period.

PROBABILITY OF AVAILABILITY: This gives JPL's estimate of the probability that the developers will be able to meet the projected availability date with adequate internal and external funding. Estimates are based upon discussions with EPRI, vendor data, and engineering judgment.

A word of caution regarding the accuracy of the data in Table 1 may be appropriate. It should be noted that the values of the cost, performance and availability parameters represent the best estimates of the various system and subsystem (including batteries) vendors and the engineering assessments of the authors. These estimates are based on a number of assumptions, some of which may be subject to question. Thus, there is a degree of uncertainty associated with these values. There is less uncertainty in more mature systems.

Also, it should be pointed out that there is no major distinction regarding uncertainties between those parameters that have narrow ranges of values and those which have fixed values. The indicated values in both cases are merely the best estimates of the vendors expressed either as a narrow range or an approximate value. There is however a distinction regarding uncertainties between those parameters that have wide ranges of values and those which have small ranges of values. Those with the wide ranges do have a larger degree of uncertainty i.e., for example the cycle life of the Zn-Br₂ Exxon system which has a two fold range of values from 2500 to 5000 cycles.

- The body of the text contains additional, detailed technical information on battery systems, other than that presented in Table 1. Included are such items as: a) a schematic diagram of each system, b) operating principles, including anodic, cathodic, and overall electrochemical reactions, c) operating temperatures, d) unit cell operating voltages for charge and discharge, e) major technical problem areas, and f) sizes of cells built to date and their performance.

B. RESULTS: BALANCE OF SYSTEM STUDY

This section summarizes the findings of the balance of system portion of the investigation.

- Table 2 presents a breakdown of balance of system costs for existing Pb-Acid storage systems. These costs are quite firm, since they have been the subject of rigorous studies. Those costs that are a function only of the power level of the system are expressed in terms of \$/kWe. Others that are a function only of energy capacity of the system are expressed in terms of \$/kWh. Still others, functions of both power and energy, are expressed in terms of both \$/kWe + \$/kWh. The total balance of system costs is \$101.2/kW + \$34.5/kWh for the existing Pb-Acid system (1979 dollars).
- Table 3 presents a summary of balance of system costs for the advanced systems. The costs are given in terms of \$/kWe + \$/kWh. The costs for the advanced Pb-Acid system are relatively firm, since they are based on realistic projections of current costs. The Fe-Air, Ni-Fe, Ni-H₂, and Ni-Zn systems are similar in configuration and would be installed in a manner similar to the advanced Pb-Acid system. Therefore, the costs for these systems are assumed identical to those for the advanced Pb-Acid system. The other advanced systems are much different in configuration and would be installed in a different manner than the above systems. No firm guidelines were available for estimating the costs for these systems, and assumptions were required to arrive at the indicated costs. (See Appendix B).

It should be noted that there is currently a number of detailed studies in process to more accurately define BOS systems costs. Detailed information was not available at the time this study was done. The basic methodology used in this study to identify BOS costs, other than the power conditioner and associated power components, is limited. As a result, there may be wide error bands in BOS costs particularly for the systems defined above as "Other Advanced Systems".

- The inverter/converter constitutes a substantial portion of balance of system costs. The cost of this component diminishes with increased bus voltage, especially in the range of 600 to 3000 volts, and also diminishes with increased power rating of the system. The indicated converter cost of \$60.50/kWe (1979 dollars) in Table 2 is for a 2200 volt bus and a 10 MWe power rating. Two types of inverter/converters were considered in this study. These are designated as line commutated and forced commutated types. Both yield comparable efficiencies of about 96% and comparable costs for advanced systems.
- Inverter/converter costs are sensitive to operation with DC bus voltage: higher DC bus voltages reflect lower costs. With advanced inverter/converter systems, it would be desirable to operate at a higher bus voltage of

**Table 2. Balance of System Costs¹ for Existing
Lead-Acid Storage Systems**

Item	\$/kWe	\$/kWh
Batt. Inst. Shipping, DC Bus		5.20
Inverter/Converter	60.50 ²	
Civil/Structural	1.00	4.20
Mechanical, Piping, Cooling		3.80
Electrical	1.00	1.10
Instrumentation	2.50	1.90
Yardwork	1.00	0.60
Distributables	4.00	2.20
Engineering Services	4.10	3.30
Subtotal	74.10	22.30
Contingency:		
11% of \$/kWe	8.15	
26% of \$/kWh		5.80
1976 Total Cost	82.25	28.10
1979 Total Cost (1.23 x 1976 cost)	101.20	34.50

¹1976 Dollars

²See Table 8-1 for inverter/converter cost -- see Appendix B for assumptions.

2200-3000 volts in order to improve balance of system economics. This study utilized costing for the 2200-3000 VDC systems only.

- Cost of the inverter/converter for the zinc-bromine and redox systems may be less expensive than the other candidate battery systems, since these systems may be charged at constant voltage, thereby reducing voltage range of the inverter/converter. These may cost 2-4% less than other candidate battery, inverter/converter systems.
- There are two reasons for increasing the energy efficiency of the battery. First, this may result in reduced component costs due to reduced power requirements. Second, more energy will be made available to the utility, possibly at reduced costs.

C. RESULTS: TOTAL STORAGE SYSTEM STUDY

A summary of findings on initial capital costs of the total storage system is given in Table 4. The indicated costs are for a 10 MWe system with 5 hours of storage capability. The highlights of Table 4 are presented in the following explanations of each column.

ELECTROCHEMICAL SYSTEMS: This identifies the type of storage system and the developer.

ELECTROCHEMICAL COST: This is the cost of the electrochemical or battery portion of the system in 1000's of 1979 dollars.

BALANCE OF SYSTEM COSTS: This is the cost of the balance of system in 1000's of 1979 dollars.

TOTAL COST: This is the cost of the total storage system in 1000's of 1979 dollars. Total costs for this size plant range from about \$2.9 million to \$9.2 million for the various systems.

Table 4 is useful for comparing the initial capital costs of the various storage systems. The table does not provide all the necessary information for making an economic comparison of the systems in an actual solar thermal plant. Two factors which influence the economics of storage systems, efficiency and cycle life, were not considered. These factors were taken into account by computing the levelized costs of delivered energy per kWh from complete solar thermal plants with the various storage systems. These costs represent the average of the distribution of all costs over the service life of the plants. (See Appendix C.) These costs take into account capital, operation and maintenance costs, and the efficiency and cycle life of the storage system.

Results of these computations are given in Table 5 for a 10 MWe (power rating) - 5 hour (storage requirement) plant with 30-year life. Columns 1, 2, and 3 give the Battery, Balance of System, and

Table 3. Balance of System Costs for Advanced Storage Systems

System	BOS Costs	
	\$/kWe	\$/kWeh
Advanced Pb-Acid	101.20	34.50
Na-S (GE)	95.12	8.15
Na-S (Ford)	95.12	8.15
Na-S (Dow)	95.12	6.25
Fe-Cr Redox (LeRC)	101.75	4.15
Zn-Cl ₂ (EDA)	105.20	5.10
LiM-FeS (Argonne)	95.12	10.20
Zn-Br ₂ (Gould)	91.90	9.25-11.15
Zn-Br ₂ (Exxon)	91.90	6.05
Zn-Br ₂ (GE)	91.90	10.95
Fe-Air (Westinghouse)	101.20	34.50
Ni-Fe (Westinghouse)	101.20	34.50
Ni-Fe (EP)	101.20	34.50
Ni-H ₂ (ERC)	101.20	34.50
Ni-Zn (Gould)	101.20	34.50
H ₂ -Cl ₂ (BNL)	95.12	15.30

Table 4. Cost of 10 MWe, 5-hr Electrochemical Storage Plant for Solar Thermal Applications (mid-1979 dollars)

Electrochemical System	Electrochemical Cost in \$1000's	Balance of System Cost in \$1000's	Total Cost in \$1000's
Advanced Pb-Acid	5800-6500	2737	8537-9237
Na-S (GE)	2150	1358	3508
Na-S (Ford)	2150	1358	3508
Na-S (Dow)	1650	1263	2913
Fe-Cr Redox (LeRC)	2420	1225	3655
Zn-Cl ₂ (EDA)	1940	1304	3244
LiM-FeS (Argonne)	2700	1462	4162
Zn-Br ₂ (Gould)	2450-2950	1382-1476	3832-4420
Zn-Br ₂ (Exxon)	1600	1221	2821
Zn-Br ₂ (GE)	2900	1466	4366
Fe-Air (Westg)	1600	2737	4337
Ni-Fe (Westg)	2700	2737	5437
Ni-Fe (EP)	3250	2737	5987
Ni-H ₂ (ERC)	3250	2737	5987
Ni-Zn (Gould)	5400	2737	8137
H ₂ -Cl ₂ (BNL)	4050	1717	5767

Table 5. Advanced Electrochemical Energy Storage Costs for a 10 MWe Solar Thermal Plant*

Storage System Costs							
Battery Type	1	2	3	4	5	6	7
	Battery Initial Cost \$/kWh	Balance of Sys. Costs \$/kWh	Total Stor. System Initial Cost \$/kWh	Storage Replacement Cost** \$/kWh	Number of Replacements	Through-Put Efficiency (%)	Levelized Cost of Delivered Energy mills/kWh
Fe-CR Redox (LeRC)	48.4	24.5	72.9	(-1.3)***	0	69	45.0
Zn-Br ₂ (Exxon)	32.0	24.4	56.4	20.7	1	74	45.2
Na-S (Ford)	43.0	27.2	70.2	27.9	1	69	48.6
Na-S (Dow)	33.0	25.3	58.3	51.5	3	90	48.7
Zn-Cl ₂ (EDA)	38.8	26.1	64.9	47.7	2	74	50.6
Ni-H ₂ (ERC)	65.0	54.7	119.7	(-1.8)***	0	70	51.8
Na-S (GE)	43.0	27.2	70.2	87.0	3	76	56.5
LiM-FeS	54.0	29.2	83.2	84.2	3	85	57.0
Zn-Br ₂ (Gould)	59.0	1.2	89.2	119.0	3	70	64.1
Zn-Br ₂ (GE)	58.0	30.0	88.0	157.0	4	75	68.6
Ni-Fe (Westg)	54.0	54.7	108.7	147.0	4	60	71.5
Ni-Fe (EP)	65.0	54.7	119.7	176.0	4	70	76.0
Fe-Air Adv.	32.0	54.7	86.7	197.0	9	50	76.5
Pb-Acid	130.0	54.7	184.7	127.0	2	85	76.7
Ni-Zn (Gould)	108.0	54.7	162.7	293.0	4	90	95.7

- Notes:
- (1) All costs are for base year 1979, in 1979 dollars.
 - (2) All values are based on a 10 MWe power plant and 5 hours of operation from storage.
 - (3) To convert the cost values to costs for the first year of commercial operation (year 2000) multiply by 3.4.

*Initial capital costs & levelized cost of delivered energy.

**Includes salvage value based on prorating residual battery life beyond 30 year plant life.

***In these cases, 97% of the originally installed battery life was used and the negative quantities correspond to a small salvage value.

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Total Storage System Initial Costs, respectively. Columns 4 and 5 consider cycle life and give Storage Replacement Costs and Number of Replacements of the battery, respectively, over a 30-year period. Column 6 gives the value of the through-put efficiency used in the computations. Finally, Column 7 gives the Levelized Costs of Delivered Energy in terms of mills/kWeh with the various storage systems. (The characteristics of the advanced solar thermal plant which is coupled to the various battery systems are given in Ref. C-4). Column 7 is used to rank the storage systems in order of economic attractiveness. The five most attractive are the Fe-Cr Redox (LeRC), Zn-Br₂ (Exxon), Na-S (Ford), Na-S (Dow), and Zn-Cl₂ (EDA) with levelized costs ranging from 45.0 to 50.6 mills/kWeh. The two least attractive are the Advanced Pb-Acid and Ni-Zn (Gould) with levelized costs of 76.7 and 95.7 mills/kWeh, respectively.

Additional results of these computations are given in Table 6 and Figure 1. Table 6 gives the Capital Investments for a 10 MWe - 5 hour plant with the various storage systems. Figure 1 gives a graphical breakdown of the levelized energy costs with the various storage systems. Therein, it is noted that the initial battery investment and battery replacement costs have an appreciable influence on levelized energy cost.

This study has identified and described existing and advanced electrochemical storage systems for solar thermal plants. Projections were made regarding cost, performance and availability of these storage systems. It was concluded that the Pb-Acid battery is the only existing cell that can meet the needs for near-term demonstration programs. Fifteen other advanced systems are under development and should be available in the 1985 to 1990 time frame. Of these fifteen, the most economically promising are the Fe-Cr Redox (LeRC), and Zn-Br₂ (Exxon) Na-S (Ford), Na-S (Dow), and Zn-Cl₂ (EDA).

Table 6. Capital Investments for 10 MWe Solar Thermal Plant with an Advanced Electrochemical Storage

Battery Type	1 Battery Initial Cost \$x10 ⁶	2 Storage Balance of System Cost \$x10 ⁶	3 Storage System Initial Cost \$x10 ⁶	4 Storage Replacement Cost* \$x10 ⁶	5 Field and Power Plant Costs \$x10 ⁶	6 All O&M Costs \$x10 ⁶
Fe-Cr Redox (LeRC)	2.420	1.225	3.645	(-0.065)**	11.24	2.858
Zn-Br ₂ (Exxon)	1.600	1.220	2.820	1.035	11.06	2.858
Na-S (Ford)	2.150	1.358	3.508	1.395	11.24	2.858
Na-S (Dow)	1.650	1.26	2.913	2.575	10.72	2.858
Zn-Cl ₂ (EDA)	1.940	1.304	3.244	2.385	11.28	2.858
Ni-H ₂ (ERC)	3.250	2.737	5.987	(-0.091)**	11.43	2.858
Na-S (GE)	2.150	1.358	3.508	4.350	11.21	2.858
LiM-FeS	2.700	1.462	4.162	4.210	10.89	2.858
Zn-Br ₂ (Gould)	2.950	1.509	4.459	5.950	11.43	2.858
Zn-Br ₂ (GE)	2.900	1.499	4.399	7.850	11.24	2.858
Ni-Fe (Westg)	2.700	2.737	5.437	7.350	11.82	2.858
Ni-Fe (EP)	3.250	2.737	5.987	8.800	11.42	2.858
Fe-Air Adv.	1.600	2.737	4.337	9.850	12.23	2.858
Pb-Acid	6.500	2.737	9.237	6.356	10.89	2.858
Ni-Zn (Gould)	5.400	2.737	8.137	14.650	10.72	2.858

- Notes:
- (1) All costs are base year 1979, in 1979 dollars.
 - (2) All values are based on a 10 MWe plant and 7 hours of storage operation.
 - (3) To convert the cost values to costs for the first year of commercial operation (year 2000) multiply by 3.4.
 - (4) The costs in columns 4, 5 and 6 are present worth values.

*Includes salvage value based on prorating residual battery life beyond 30 years plant life.

**In these cases, 97% of the originally installed battery life was used and the negative quantities correspond to a small salvage value.

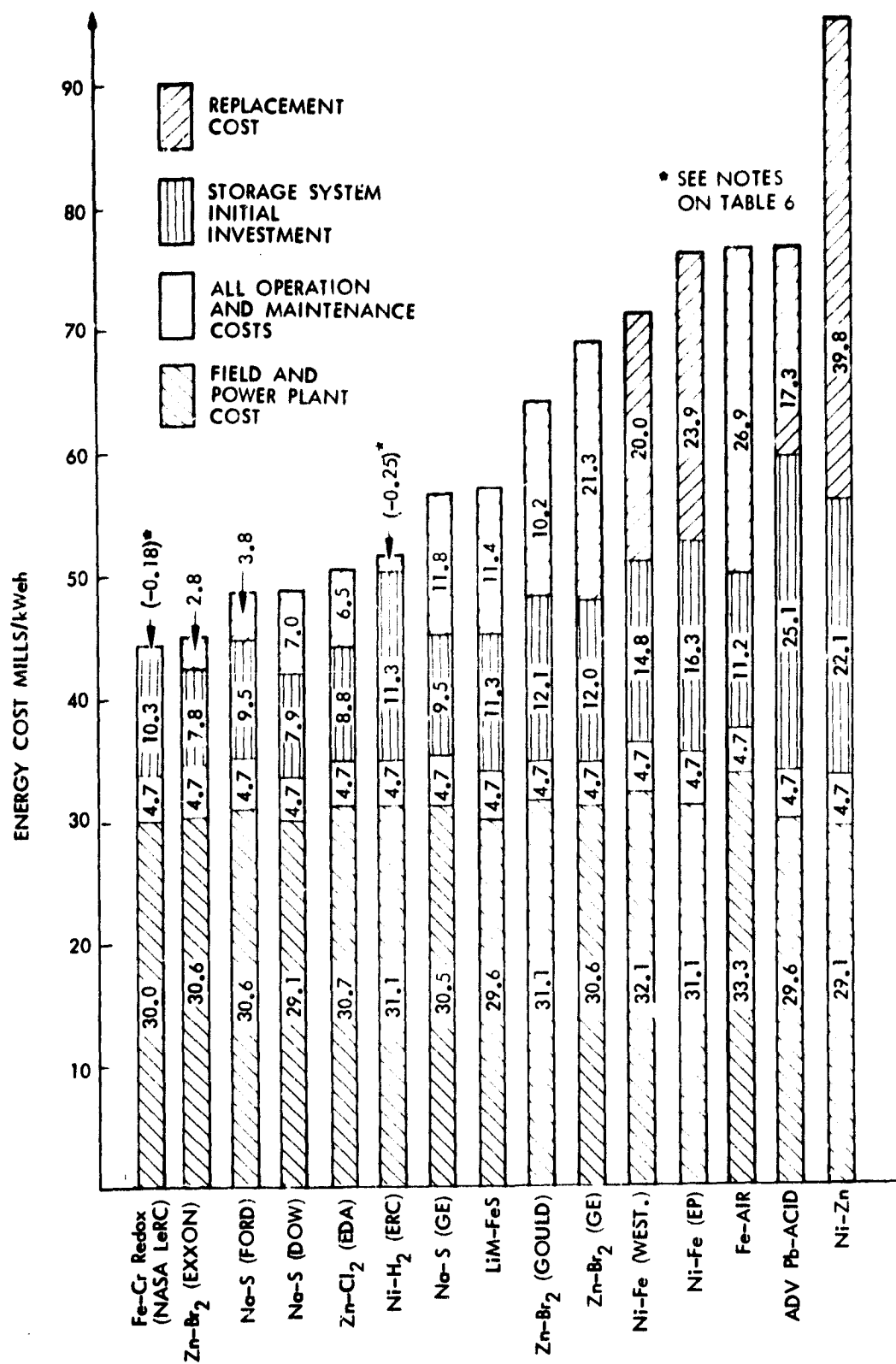


Figure 1. Levelized Energy Cost of Various Storage Systems for a 10 MWe Solar Thermal Plant Showing Contributing Cost Factors

SECTION I

INTRODUCTION*

There are several types of energy storage systems that could be considered for use in conjunction with solar thermal plants. Among these storage types are thermal, electrochemical, pumped hydro, compressed gas, flywheels, and superconducting magnetic systems.

In this report, only the electrochemical storage has been considered and the term energy storage is taken to mean only electrochemical storage. The decision to incorporate a storage system in a solar thermal plant is dependent on many factors. Among these are: a) the solar input profile, b) whether or not the plant is a "stand alone" plant, c) the availability of fossil fuels, d) the duty cycle of the system, e) the capital cost of the system, f) the operational life of the system, g) the cycle life of the system, h) the round-trip energy efficiency of the system, i) the maintenance requirements of the system, and j) the scrap value of the system. A valid judgment of the economic attractiveness of incorporating a storage system in a solar thermal plant is possible only when all of these factors are known.

During the past several years, activity in the field of electrochemical storage and inverter/converter technology has increased. This is attributed, in large part, to the intended use of electrochemical systems for utility load leveling and electric vehicle propulsion applications. Work is underway at laboratories throughout the country and abroad to improve the existing Pb-Acid batteries and develop unique, low-cost advanced electrochemical systems for those applications. In addition, substantial efforts are underway to develop advanced inverter/converter systems for use in the battery system. Progress in the field has been rapid and has proceeded to the point where demonstration plants and vehicles are under development.

The objective of this investigation was to assess the status of existing and advanced electrochemical storage systems and inverter/converter technologies for solar thermal applications. The resultant findings would enable JPL's Solar Thermal Power Systems Project to evaluate the impact of electrochemical storage systems on near- and far-term solar thermal plants.

The approach consisted of three steps. First, a review was made of the existing literature on electrochemical storage and inversion/conversion systems. Second, discussions were held with the manufacturers and developers of these systems to obtain an update on the status of these systems. Third, the information collected was reduced, tabulated, and analyzed in this report. A glossary of terms frequently used is provided in Appendix F.

*References 5, 8.

SECTION II

ELECTRICAL POWER PROCESSING CONSIDERATIONS FOR A SOLAR THERMAL ELECTRIC PLANT*

Each Solar Generation Unit (SGU) has all the components necessary for conversion of solar energy to electrical energy. The concentrator and receiver together collect all the sun's energy that is available to the system. A short-term thermal storage and transport system is used to provide a partially smoothed heat input to the heat engine. The heat engine in turn converts the heat input into mechanical action which powers a generator. The output of the generator is used to charge the batteries and to feed power to the plant output bus. The batteries store energy to be used when solar inputs are diminished or unavailable. Protection and harmonic reduction capabilities are also provided.

Whether SGU output power is fed into the electric utility bus or a local stand-alone load, AC output voltage is required. However, a battery used for storage of electrical energy requires DC voltage at the battery interface, so power processing equipment must be provided to convert DC battery voltage to AC (SGU) output voltage. The remaining electrical interface is at the generator output and can be either AC or DC, depending on the design approach selected.

In the case of the AC approach, an AC generator is selected. A portion of the power generated is fed to the AC output bus. The remaining portion of generator output power is processed by an AC-to-DC converter to charge the battery. Conversely, when the energy stored in the battery is required, a DC-to-AC inverter transfers energy from the battery to the SGU output bus. Since battery charging and discharging are inverse operations and are not required simultaneously, the inversion and conversion functions can be provided in a single bidirectional converter/inverter unit. Either a conventional AC generator (induction generator or synchronous generator) or a special AC generator may be used for the AC approach. A Field-Modulated Alternator (FMA) is an example of a special AC generator. The FMA is basically a power amplifier with a reference signal coming from the AC utility bus. A cycloconverter used in conjunction with a high frequency alternator is another example of a special AC generation system.

Figure 2-1 shows an example of a conceptual design for a SGU for the AC approach (AC-link) utilizing a conventional AC generator and bidirectional converter/inverter. Bidirectional converter/inverter units are manufactured by Garrett Corp., United Technology Corp. and Westinghouse Corp. These units are primarily developmental types. Also, a power-conditioning configuration consisting of a separate battery charger and a separate inverter are available commercially from companies such as ESB, Inet and Emerson Electric.

*References 10, 16.

The units manufactured by ESB, Inet and Emerson Electric are utilized primarily in applications requiring uninterruptible power or as frequency changers. AC critical bus backup is provided by lead calcium batteries of limited cycle life with battery backup ranging from ten minutes to one hour. Uninterruptible power supplies are manufactured on a large scale and have achieved exceptional levels of reliability. Generally, the range of DC bus voltages is 300 to 600 VDC.

Utility interface voltages for uninterruptible power supplies are generally at 480 VAC above 500 kWe. Maximum system size for uninterruptible power supplies is typically 2.5 MWe, although an 8 MWe system is on order with ESB for the Social Security Administration. These systems are generally modularized with built-in redundancy. For the 10 MWe solar thermal plant, utility interface voltage will be at 13.8 KV or higher. The actual interface voltage is system dependent and may vary according to the available utility distribution bus.

In the case of the DC approach either a DC generator or a conventional AC alternator/rectifier is used to generate DC power. A portion of the DC generator power is fed into the DC-to-AC inverter and subsequently to the AC output bus. The remaining DC power from the generator output is used to charge the battery. The generator is controlled to obtain a proper battery charging profile. When the energy stored in the battery is required, a DC-to-AC inverter transfers energy from the battery to the SGU output bus. Since both the generator and battery provide DC power, a single inverter can provide power to the AC output if the battery can be connected directly to the generator DC output. An example of a conceptual design for a SGU using the DC approach (DC-link) is shown in Figure 2-2.

For the purposes of this battery study, the AC-link design will be the only one considered because of its higher efficiency and lower cost.

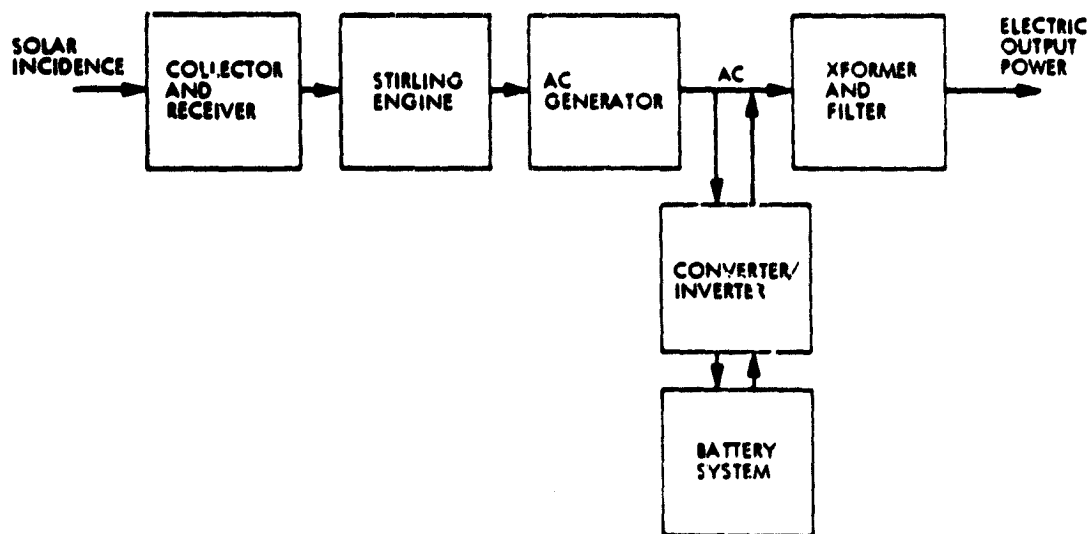


Figure 2-1. Block Diagram of a Solar Generation Unit for the AC-Link Approach Using a Conventional AC Generator

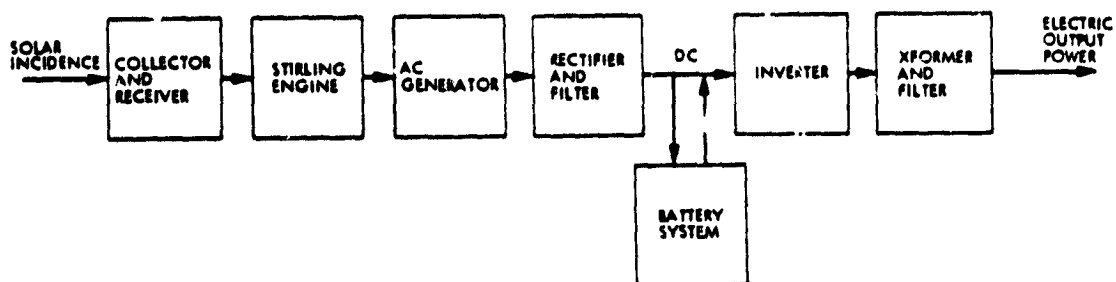


Figure 2-2. Block Diagram of a Solar Generation Unit for the DC-Link Approach Using a Conventional AC Generator

SECTION III

AN AC-LINK SYSTEM FOR A 10 MWe SOLAR THERMAL PLANT WITH FIVE HOUR BATTERY STORAGE*

An AC-link solar generation system required to provide an output of 10 MWe will require a multiplicity of solar generation units (SGU). The power outputs of the solar generation units will be summed, transformed, and transferred to the utility grid. Electro-chemical energy storage is provided by an inverter/converter that both interfaces the battery with the utility grid and charges the battery as required. The primary methods of battery charging are: battery charging by the SGU, and battery charging by the utility grid during times of minimal utility usage. The solar generation system shown in single-line diagram Figure 3-1 consists of three subsystems: a) generator/circuit breaker/contactor, b) utility interface, and c) storage.

A. GENERATOR/CIRCUIT BREAKER/CONTACTOR

These components comprise the electrical power train of the 15 kWe solar thermal plant, which consists of collector, receiver, Stirling engine and electric generator with appropriate disconnect and protective devices. The three phase outputs of these module groups are summed at a 480 VAC level and transformed to the appropriate utility bus. The magnitude of generator voltage is limited by low kWe generator output. This restriction is related to the availability of standard designs, and the code and cost restrictions above 600 VAC, three phase. The voltage level of the AC bus will affect plant cable costs and interfacing switchgear and disconnects relating to the inverter/converter module. Also, the cost of the AC bus system connection to the utility will be affected by the intertie voltage level. Multiple collection transformers will be used in order to minimize both transformer cost and plant cable cost.

B. UTILITY INTERFACE

The utility interface consists of a transformer, filter, controls and associated switchgear. The output of the summed module groups is voltage conditioned (voltage is stepped up) by the utility interface and power is delivered to the utility. The transformation voltage will be determined by the utility intertie voltage.

*References 11, 13.

C. STORAGE SYSTEM

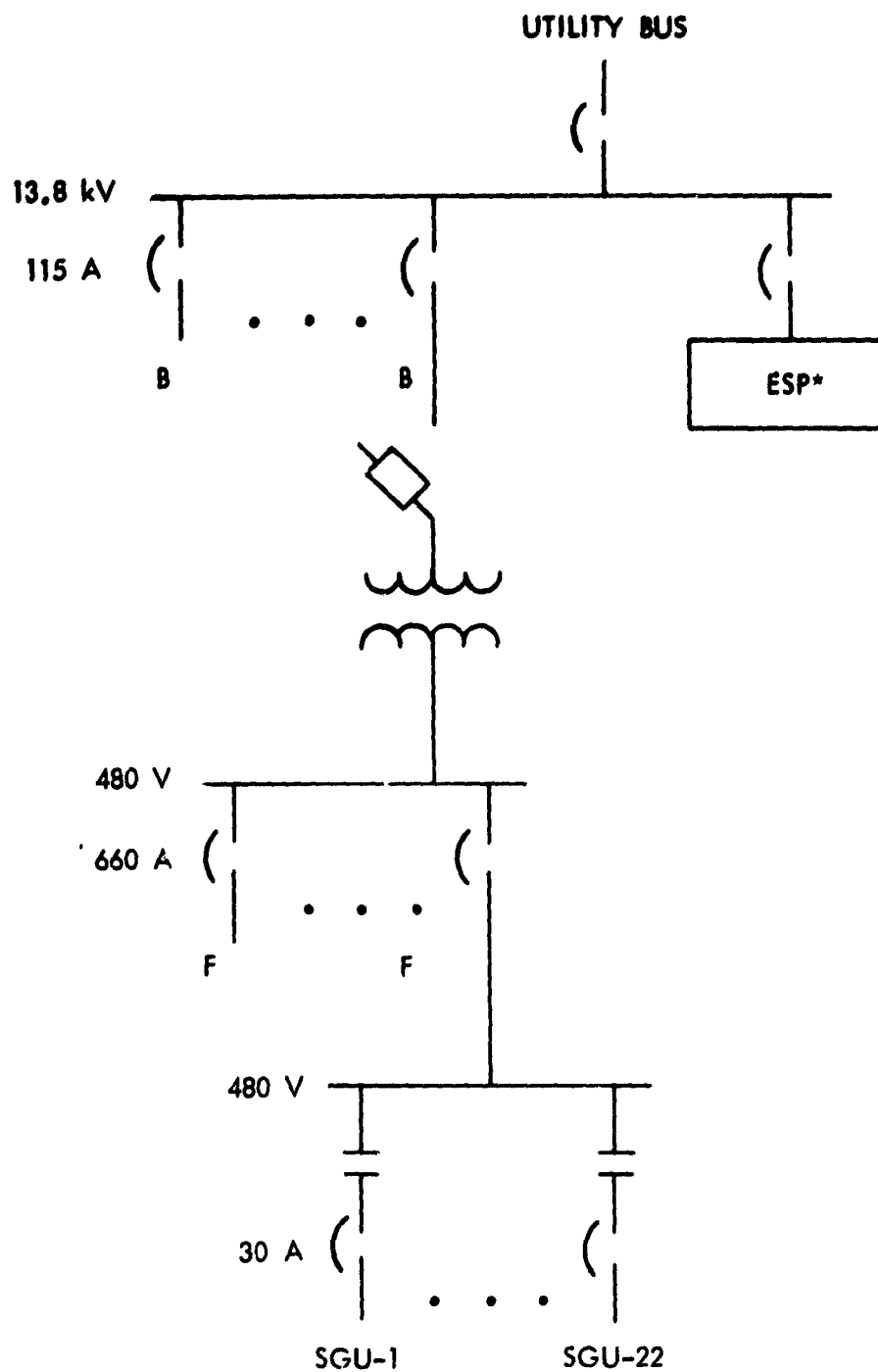
The storage system is available to provide energy to the utility when solar insolation is low or not available. The storage system consists of the following components (shown in Figure 3-1).

- (1) Battery disconnects: These disconnect batteries for battery maintenance.
- (2) Fuses: These protect battery and interconnecting cables.
- (3) Battery: The battery voltage level and requirements are detailed in Section IV. The number of battery parallel strings will be determined as a function of battery module size defined by the battery manufacturer, DC bus voltage and the MWe battery rating.
- (4) Inverter: The inverter module will provide energy to the utility when the solar insolation is insufficient or unavailable. Energy from the battery is delivered to the utility through the inverter to a maximum of 10 MWe. The total energy delivered from the inverter system is 50 MWeh on a daily basis.

The inverter/converter acts as a battery charger when the batteries require recharge. This is accomplished in a controlled manner with provision for current or voltage regulation. Battery charging profile will be determined by programming of the converter in the battery charging mode. Battery recharge will occur over a period of ten hours.

- (5) Inverter/Converter Interface: The inverter is provided with protective circuit breakers, disconnects and fuses. The disconnects and the circuit breakers are provided for the maintenance of the inverter/converter. In addition, a transformer is provided to interface the inverter/converter with the high voltage, AC bus of the plant. The transformation voltage will be determined by the inverter/converter design and the desired DC bus voltage of the battery.

In addition, this discussion and block diagram (Figure 3-1) are also generally applicable to 0.1 MWe and 1 MWe plants. Differences will be in the number of generators used, inverter/converter size, energy storage capability of the battery, power collection methodology, cables, transformers, plant size, switchgear and disconnects. The energy delivered to the utility will be .5 MWeh, 5 MWeh, and 50 MWeh, respectively for the .1 MWe, 1 MWe and 10 MWe solar thermal plants having a five-hour storage requirement per day.



*ESP - ELECTRIC STORAGE PLANT
(SEE Fig. 7-1)

Figure 3-1. Single-Line Solar Thermal Plant Diagram

SECTION IV

BATTERY/SYSTEM CONSIDERATIONS AND ELECTRICAL CHARACTERISTICS*

The battery constitutes the primary source of energy storage for the system discussed. The selection of an AC-link design offers several opportunities for differing system configurations. From the viewpoint of the utility, a given peak power and energy storage capacity on the grid may be composed of a single plant, containing a number of modules or the same number of modules may be dispersed at a number of locations throughout the system. However, with the DC-link system it is advisable to have the storage system at the same location as the solar thermal plant. This is due to the cost of providing a separate DC cable intertie to the remotely connected battery storage plant. It is also possible with an AC-link system to have various dispersed solar thermal plants connected to a grid and a central energy storage system. This will reduce transmission losses and substantially reduce plant and maintenance costs since energy storage will be at one location and not dispersed. For the system described in this study, a single battery storage system will be integrated with the solar thermal plant. Energy for battery charging will be provided by the solar generation units.

The battery system specification is detailed to encompass three battery voltage levels. The lower level, 600 VDC, is described here due to the present availability of inverter/converter equipment. The 1200 VDC and 2200 VDC battery voltage levels are considered for low inverter/converter cost. As high voltage technology develops, systems ranging from 2000-3000 VDC will become readily available resulting in balance of system (BOS) cost reduction. Currently, high voltage systems are in process for installation at the BEST facility in New Jersey and for the 4.8 MW fuel cell system at Consolidated Edison. These systems are for utility load-leveling purposes. There will be little effect on battery cost due to the difference in battery voltage level since battery costs at these energy and voltage levels are predicated on energy storage. System voltage will affect other costs (such as switchgear, inverter/converters, cable, etc.).

Battery energy efficiency is a significant parameter in relation to system design and cost. Higher efficiency battery systems may reflect in the following:

- (1) Battery charger kilowatt requirement is reduced.
- (2) Battery charger cost may be reduced.
- (3) Switchgear and disconnects for battery and charger may be reduced in current handling capacity. This may result in reduced battery plant costs.

*References 12, 7.

- (4) Cabling and connections may be reduced in size resulting in possible cost reduction.
- (5) Increased amounts of energy will be made available to the utility, resulting in reductions in cost of delivered energy.

Prior to identifying battery costs and technical considerations, a battery configuration questionnaire was developed. This questionnaire is included in Appendix A of this study. Sample battery/system specifications are provided in Table 4-1*a-c.

Table 4-1a. Sample Battery/System Design Specifications

Design	Power Output	Current Max (Battery)
A	.1 MW	220 amps for 600 VDC System 100 amps for 1200 VDC System 50 amps for 2640 VDC System
B	1 MW	2130 amps for 600 VDC System 1065 amps for 1200 VDC System 485 amps for 2640 System
C	10 MW	20850 amps for 600 VDC System 10420 amps for 1200 VDC System 4735 amps for 2640 System

Table 4-1b. Battery Terminal Voltage Specifications

VDC System	Max Recharge Voltage	Nom. Voltage	End of Discharge Voltage
600	745	600	500
1200	1490	1200	1000
2200	3280	2640	2200

*Table 4-1 contains preliminary specifications for lead-acid battery systems (Reference 4). Specifications for other advanced batteries will be similar, except for maximum currents and DC voltage range (see Section VI).

Table 4-1c. General Battery/System Specifications

-
- Depth of Discharge: The percentage of rated capacity that is removed during discharge. Depth of discharge is 80%.
 - DC Voltage Range*: The ratio of maximum to minimum voltage during battery operation is:
 - 1.49:1 from top of charge to end of discharge.

The maximum to minimum voltage ratio during battery discharge is:

 - 1.2:1 from top of discharge to end of discharge.
 - Discharge Time: 5 hours
 - Recharge Time: 10 hours (approximate)
 - Charge Profile: Battery may be charged under the following modes as required by system power management:
 - Constant power
 - Constant voltage
 - Constant current
 - Variable power as provided by available insolation characteristics
 - Temperature Effect: DC voltage ranges and energy storage capacity will be altered due to ambient temperature changes. Worst case conditions should be specified. Batteries will be cooled in order to optimize cycle life.
-

*Operational voltage range will vary from equalizing charge voltage to voltage level at 80% depth of discharge.

SECTION V

STATUS, PERFORMANCE, AND COST OF EXISTING LEAD-ACID BATTERIES*

A cutaway view of a typical lead-acid battery suitable for solar thermal applications is given in Figure 5-1. Also shown are the electrochemical reactions that take place within this system during charge and discharge. This particular type of lead-acid battery is classified as a "motive power" or "traction" battery. It is specifically designed for repetitive deep discharges at moderate to high power densities on a daily 6 to 8 hour basis. Its plates are somewhat thicker than those of a conventional car-starting battery which is specifically designed for repetitive shallow discharges at extremely high power densities. The positive plates of the motive power type battery are wrapped with special materials to inhibit shedding of the positive active material which is a primary cause of failure in this type of battery. A recent innovation with this type of battery is the use of lead-calcium rather than lead-antimony grids. This change results in markedly reduced gassing rates and hence less watering and maintenance requirements.

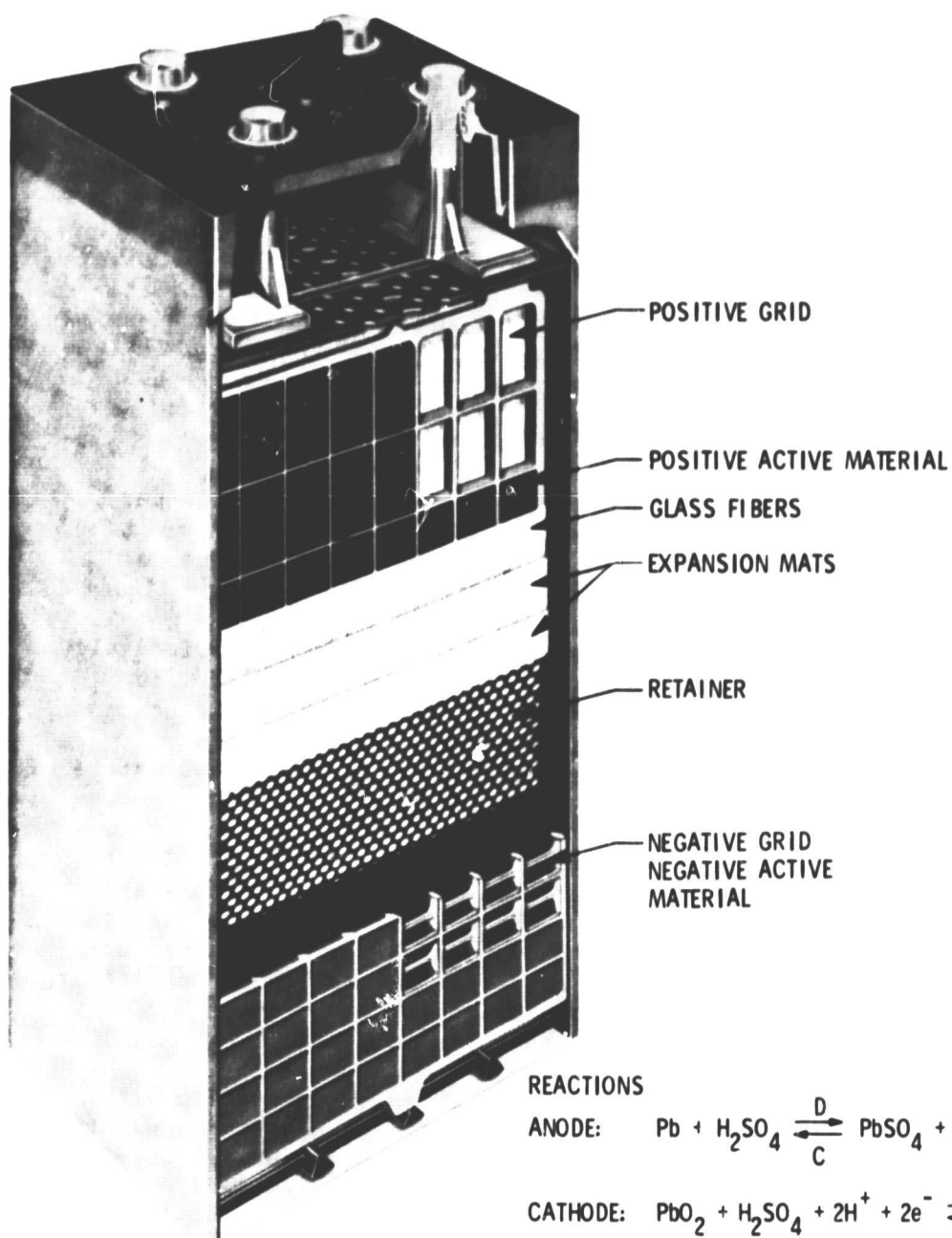
Normal discharge voltage for this battery is 1.9 volts per cell. End of discharge voltage is 1.75 volts per cell and nominal charge voltage is 2.1 volts per cell. End of charge voltage is usually 2.4 volts per cell.

This battery requires an equalization type charge periodically (every one to three weeks depending on the manufacturer). This usually consists of an overnight charge at low rates until the voltages of all cells reach 2.6 volts. The purpose of this equalization charge is to bring all cells to a full and equal state of charge.

The batteries operate best at ambient temperatures of 15° to 25°C. Available capacity and power is diminished appreciably at temperatures below 0°C. Power and available capacity increase at elevated temperatures of 40°C and above, but life is shortened at these elevated temperatures. The batteries generate heat on discharge and overcharge at a rate that is proportional to current. The batteries must be air or water cooled in large sizes.

Cycle life of lead-acid batteries varies exponentially with depth of discharge; the greater the depth of discharge the lower the cycle life. A plot of cycle life versus depth of discharge supplied by a manufacturer for one type of motive power battery indicates the following:

*References 20, 21.



REACTIONS

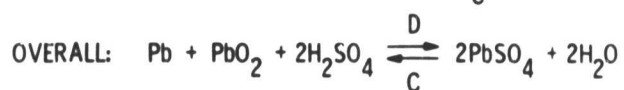
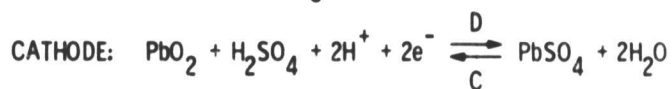
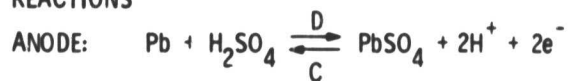


Figure 5-1. Existing Lead-Acid Batteries

Depth of Discharge %	Number of Cycles
80	2000
60	4300
40	8500
20	17000

For solar thermal applications, the manufacturers recommend operation at 80% depth of discharge, at which the batteries will deliver 2000 cycles and have an operational life of 10 years.

Within the United States there are four large and several smaller manufacturers of this type of lead-acid battery. The four major ones are C&D, Globe Union, ESB, and Gould.

Cost and delivery estimates of batteries for two different types of solar thermal plants were obtained from the large manufacturers. In one case, the batteries were to deliver 800 kWe for 1 hour on a daily basis. The unit cost of these batteries ranged from \$190 to \$220/kWh of delivered energy and delivery time was estimated at six months. In another case, the batteries were to deliver 1 MWe for 5 hours on a daily basis. The unit cost of these batteries was near \$170 kWeh and delivery time was again six months.

The reason for the difference in the above unit costs is explained on the basis of discharge time and utilization of active materials. For short discharge times, such as the one hour rate, the utilization is quite low, while for longer discharge times such as the five hour rate, the utilization is appreciably greater. On this basis, it is necessary to employ more active materials, in effect more batteries, to deliver a given output for the shorter discharge time than for the longer discharge time. Hence, the cost per unit of output is larger for the shorter discharge times than for the longer discharge times.

Two of the large manufacturers were questioned about their surplus production capability. This is their ability to produce additional batteries above their current annual production without major expansion of their existing facilities. One company replied that they could produce an additional 50 to 80 MWeh worth of batteries per year. Another reported they could produce an additional 50 MWeh worth of batteries per year.

The round-trip energy efficiency of existing lead-acid batteries ranges from 70% to 85%. The lower efficiencies are associated with the shorter discharge times and the higher efficiencies are associated with the longer discharge times.

The floorspace requirements of a battery is expressed in terms of its "footprint" or energy per unit area. The footprint for existing lead-acid batteries is 50 to 55 kWeh/m².

SECTION VI

STATUS, PERFORMANCE, AND COST OF ADVANCED ELECTROCHEMICAL SYSTEMS

A. ADVANCED LEAD-ACID BATTERIES*

Several battery manufacturers are currently in the process of developing advanced lead-acid batteries for utility and electric vehicle applications. These advanced batteries are expected to perform better, have lower maintenance requirements and cost less than existing lead-acid batteries.

The manufacturers are examining several new approaches to develop these advanced lead-acid batteries. One of these approaches involves modification of grid geometry to provide equal potential distribution across the surface of the grid and thereby provide uniform current density. Another involves use of composite grid materials, such as lead-plastic composites, in place of solid lead grids. This change is expected to markedly reduce lead usage and hence cost, and also minimize grid corrosion which can limit life. The use of new alloying agents on the grids to minimize gassing, and hence watering and maintenance requirements is another approach. An alternate method involves use of additives to the positive and negative active materials to improve and maintain utilization of the active materials over the long term. Modification of processing variables for preparing the active materials and applying them to the grids to improve uniformity of the resultant plates and reduce fabrication time and cost is another method. The use of electrolyte circulation techniques to insure uniform concentration of acid throughout the cells and thereby improve utilization is another possibility. A final approach involves use of internal gas recombination devices to recombine evolved H_2 and O_2 to H_2O and thereby minimize watering and maintenance requirements.

Operating charge and discharge voltages of the advanced cells will be the same as for existing lead-acid cells. Equalization charges will be required for the advanced cells but perhaps not as frequently as for the existing cells. Operating temperatures and cooling requirements for the advanced cells will be the same as for the existing cells. Round-trip energy efficiencies are expected to range from 80% to 85%.

It is anticipated that the advanced batteries will be manufactured in dedicated plants with production rates of about 1000 MWeh/yr of batteries.

*References 20, 21.

Cost estimates for these batteries from three leading manufacturers range from \$116 to \$130/kWh in 1979 dollars.

Cycle life of these advanced batteries is expected to be 4000 cycles at 80% DOD as compared with 2000 cycles at 80% DOD with existing batteries. The batteries will be capable of delivering 100% of rated output after 4000 cycles. Operational life of the advanced systems is expected to be 20 years as opposed to 10 years for existing batteries.

Footprint of the advanced batteries is expected to be 75 kWh/m² as opposed to 50-55 kWh/m² for existing batteries.

It is projected that these advanced lead-acid batteries will be available by 1985, pending continuance of existing funding levels.

B. SODIUM SULFUR SYSTEM

1. General Electric*

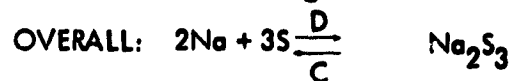
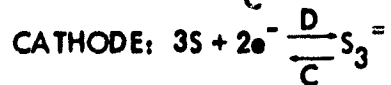
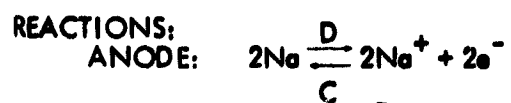
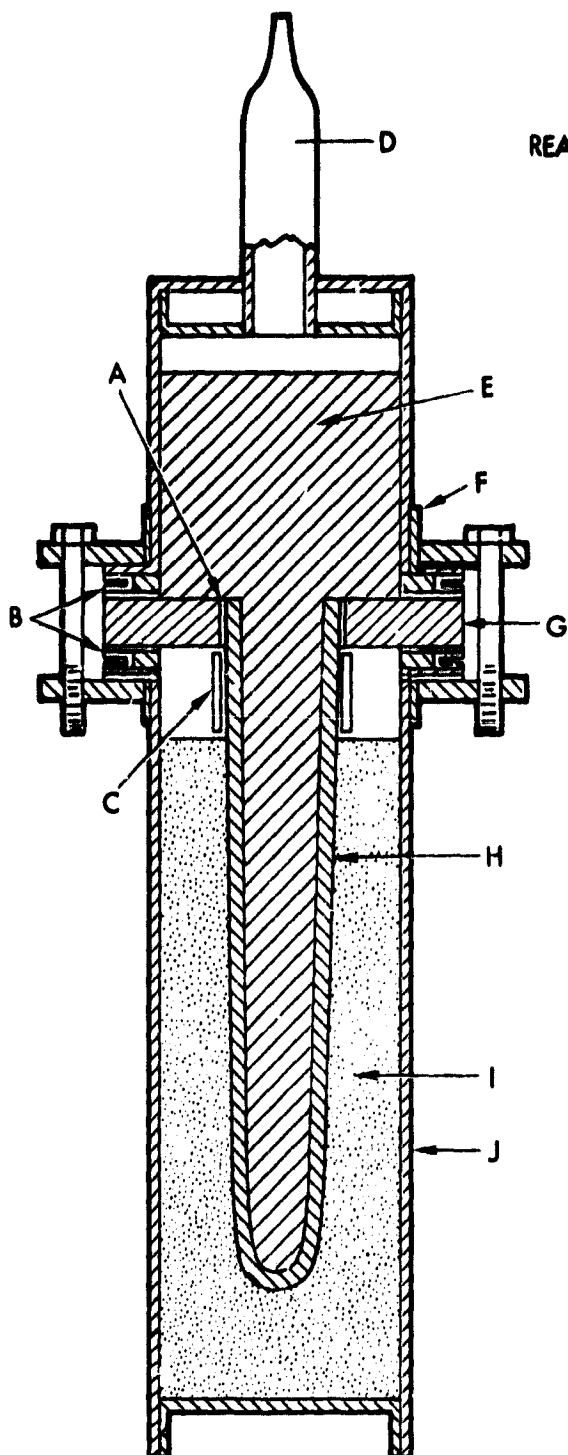
A diagram of General Electric's sodium-sulfur cell is given in Figure 6-1. Also shown are the electrochemical reactions that take place within the cell during charge and discharge. The cell operates at a temperature of 350°C at which the reactants, sodium and sulfur, are in the molten state. A key element of the cell is its beta alumina separator. This separates the sodium and sulfur compartments and transports sodium ions from the sodium to the sulfur compartment during discharge and back during charge.

Nominal discharge voltage for this cell is 1.7 volts. End of discharge voltage is 1.6 volts. Nominal charge voltage is 2.2 volts. End of charge voltage is 2.3 volts.

Areas of concern with this cell are cracking of glass and ceramic seals, corrosion of the metal container by polysulfides, and long-term stability of the beta alumina separator. Failure of the beta alumina separator could result in mixing of molten sodium and sulfur and subsequent exothermic chemical reaction between the two. This has apparently not been a problem for General Electric to this point.

A substantial program is underway at General Electric to develop this system for load-leveling applications. The total number of personnel involved on the program is near 50 and the funding level is about \$5M per year. The program is designed to establish technical and manufacturing feasibility of large-scale, sodium-sulfur systems. In January 1979, General Electric developed their first parallel-connected bundle of 40 full-size cells each with capacity of 300 Weh. The company plans to complete testing this bundle during

*Reference 22.



Na-S TEST CELL

- A- GLASS SEAL
- B- MECHANICAL SEAL
- C- GLASS SPACER
- D- LOADING TUBE
- E- SODIUM
- F- INSULATOR
- G- ALPHA ALUMINA RING
- H- BETA ALUMINA TUBE
- I- SULFUR AND CARBON FELT
- J- METALLIC CONTAINER

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Figure 6-1. Sodium Sulfur Cell (General Electric)

1979. The company also plans to initiate accelerated life-cycle tests to demonstrate a minimum of six-year life. In addition, the company is planning a large-scale demonstration in the BEST facility by 1983.

Projected cost of the General Electric sodium-sulfur battery modules in large-scale production is about \$43/kWeh. Round-trip energy efficiency is estimated to be about 76%. Cycle life is expected to be at least 2500 cycles at 80% DOD.

Pending continuance of existing funding levels, it is anticipated that the General Electric system will be available by 1985.

2. Ford*

A diagram of Ford's sodium-sulfur cell is given in Figure 6-2. Also shown are the electrochemical reactions that take place within the cell during charge and discharge. The cell is quite similar to the General Electric cell. It operates at a temperature of 350°C, at which the reactants, sodium and sulfur, are in the molten state. A key element of this cell is its beta alumina separator. This separates the sodium and sulfur compartments and transports sodium ions from the sodium to the sulfur compartment during discharge and back during charge.

Nominal discharge voltage for this cell is 1.7 volts. End of discharge voltage is 1.6 volts. Nominal charge voltage is 2.2 volts. End of charge voltage is 2.3 volts.

Areas of concern with this cell are the same as with the General Electric cell. These are cracking of glass and ceramic seals, corrosion of the metal container by polysulfides, and long-term stability of the beta alumina separator. Failure of the beta alumina separator could result in mixing of molten sodium and sulfur and subsequent exothermic chemical reaction. This has not been a problem for Ford to this point.

A substantial program is underway at Ford to develop this system for electric vehicle propulsion and for load-leveling applications. The total number of personnel involved ranges from 36 to 72, and the funding level is near \$5M per year. The program includes continuing research on materials for cell components, life-cycle testing, scale up of cell size, and development of manufacturing facilities. The company has demonstrated 800 cycles on a single cell. They have now scaled up to a 200 Weh unit cell size. They are planning to demonstrate a 1 MWe-5 hour unit in the BEST facility by 1983. In addition, Ford is planning an electric vehicle demonstration of their system in the near future.

*Reference 23.

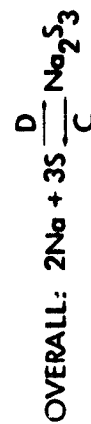
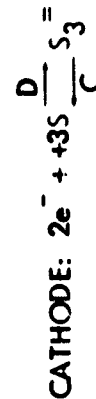
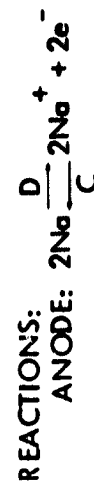


Figure 6-2. Sodium Sulfur Cell (Ford)

Projected cost of the Ford sodium-sulfur battery modules is greater than \$43/kWeh. It is not possible to accurately project how much greater than \$43/kWeh it will be at this time. Round-trip energy efficiency is estimated to be 75%. Cycle life is expected to be in the range of 2500 to 5000 cycles at 80% DOD. Pending continuance of existing funding levels, it is anticipated that the Ford system will be available by 1985.

3. Dow*

A diagram of the Dow sodium-sulfur cell is given in Figure 6-3, which also shows the electrochemical reactions that take place within the cell during charge and discharge. The cell is similar to those of General Electric and Ford, in that it employs the same electrochemical couple. The major difference, however, is that the Dow cell employs thin, sodium-ion conducting glass as a separator instead of beta alumina. The glass offers higher resistance to sodium ion transport than the beta alumina. To compensate for this, the Dow cell is configured with a high surface area by employing bundles of thin-wall, very small diameter, hollow glass fibers. Sodium ions are transported from the inside to the outside of the glass fibers during discharge, and from the outside to the inside during charge. The cell operates at 300°C.

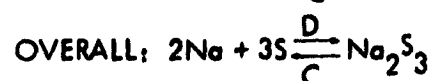
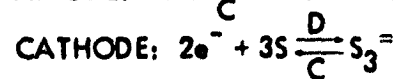
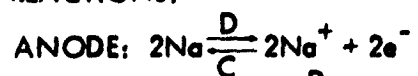
Nominal discharge voltage for this cell is 1.7 volts. End of discharge voltage is 1.6 volts. Nominal charge voltage is 2.2 volts. End of charge voltage is 2.3 volts.

The major area of concern with the Dow cell is breakage of the tiny hollow fibers which are 50 micron ID and 70 micron OD. Breakage causes mixing of molten sodium and sulfur, chemical reaction between the two, and ultimate cell failure. Another area of concern is the complex and intricate manufacturing problem of attaching the thousands of tiny fibers to the header or "tubesheet" as it is called by Dow. This major problem area was taken into account in arriving at a low probability of availability in Table 1. Also of concern is start-up and shut-down of the cell, which has not been demonstrated to withstand thermal cycling at this point.

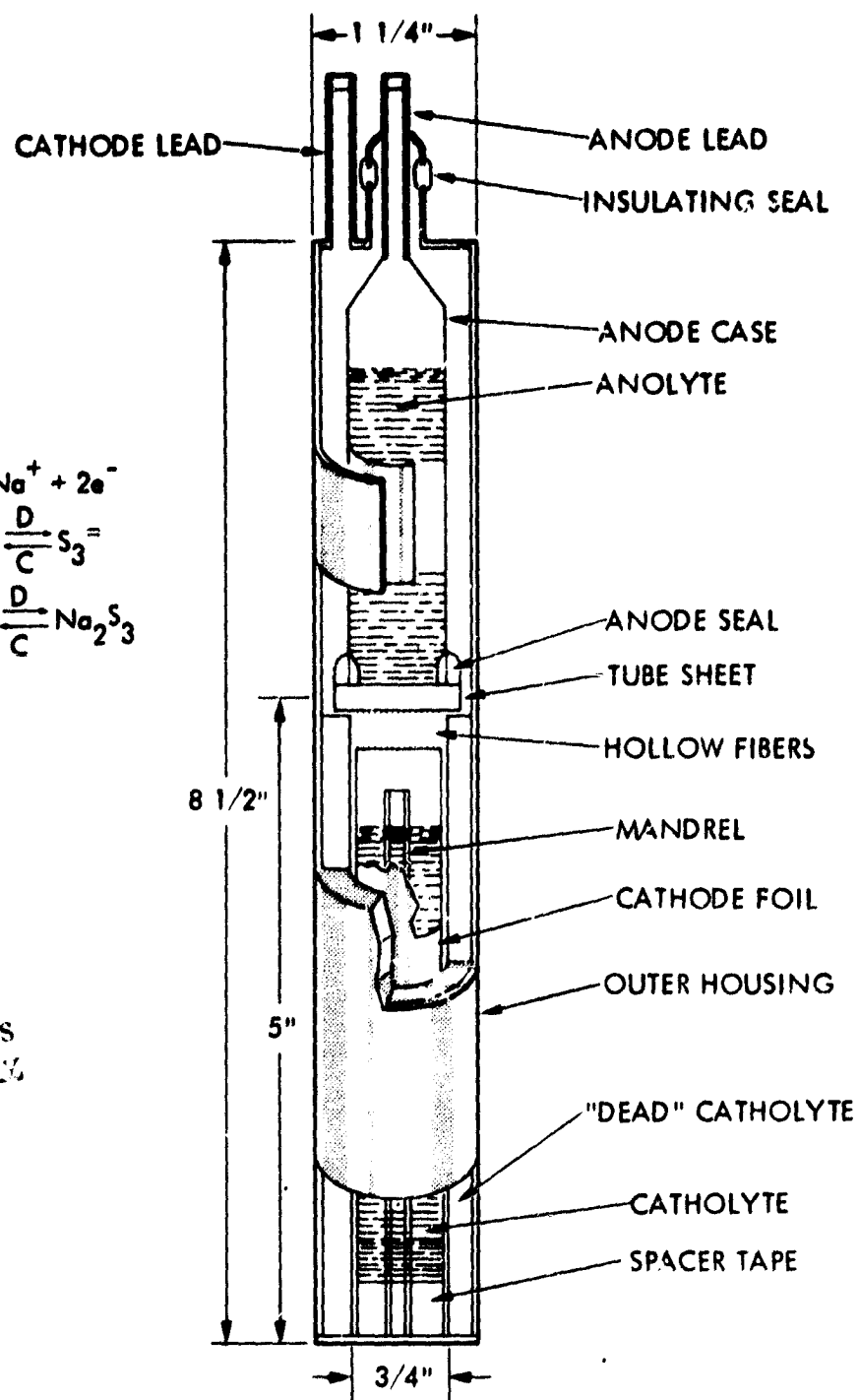
A program is underway at Dow to develop this system for load-leveling applications. The total number of personnel involved is 15 and the funding level is about \$1.6M per year. Current emphasis of the program is divided into two areas. The first of these is to scale up from the existing 6 AH, 12 Weh size to the 40 AH, 80 Weh size. The second is to develop a battery based on the 6 AH, 12 Weh size cells. Previously, Dow ran a 0.5 AH cell continuously for 1.1 years and it delivered 9000 cycles at 30% DOD. Also, Dow ran another 0.5 AH cell continuously for 5.5 months and it delivered 3800 cycles at 90% DOD. Cycle life of the 6 AH cells, however, has been found to be much less than the above.

*Reference 24.

REACTIONS:



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6 AMPERE-HOUR CELL DESIGN

Figure 6-3. Sodium Sulfur Cell (Dow)

Projected cost of the Dow sodium-sulfur battery modules is approximately \$33/kWeh. Round-trip energy efficiency is estimated to be 90%. Cycle life is expected to be 3000 cycles at 80% DOD. Pending continuance of existing funding levels, it is anticipated that the system will be available by 1990.

C. IRON-CHROMIUM REDOX SYSTEM -- NASA LEWIS RESEARCH CENTER*

A schematic diagram of NASA Lewis Research Center's (LeRC) iron-chromium redox system is given in Figure 6-4, which also shows the electrochemical reactions that take place within the system during charge and discharge. The system is different than most conventional batteries in that its "active materials" are electrolyte solutions which are stored externally in tanks and pumped to the cell or power conversion section during operation. Each unit cell is comprised of an anode compartment with an inert electrode and a cathode compartment with an inert electrode. The two compartments are separated by an ion-selective membrane which permits transport of chloride ions to maintain charge neutrality. In a practical battery the cells are connected electrically in series while electrolytes are transported into and out of their respective compartments in a parallel flow manner.

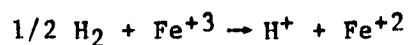
Three unique features of the system are its trim cells, open-circuit cell, and rebalance cell. The trim cells contain valves in their electrolyte inlet ports. Near the end of discharge, when overall voltage begins to decline, these valves are opened to provide additional voltage and maintain essentially constant overall discharge voltage. Similarly, near the end of charge when overall voltage tends to increase, these valves are closed to reduce voltage and provide essentially constant overall charge voltage. The voltage of the open-circuit cell is a direct measure of the concentration of electrolyte and, hence, may be used to indicate state of charge. The rebalance cell is used to recombine small amounts of hydrogen that are evolved at the chromium electrode during charge. The anode compartment of the rebalance cell contains a fuel-cell type electrode where the hydrogen is oxidized according to the reaction:



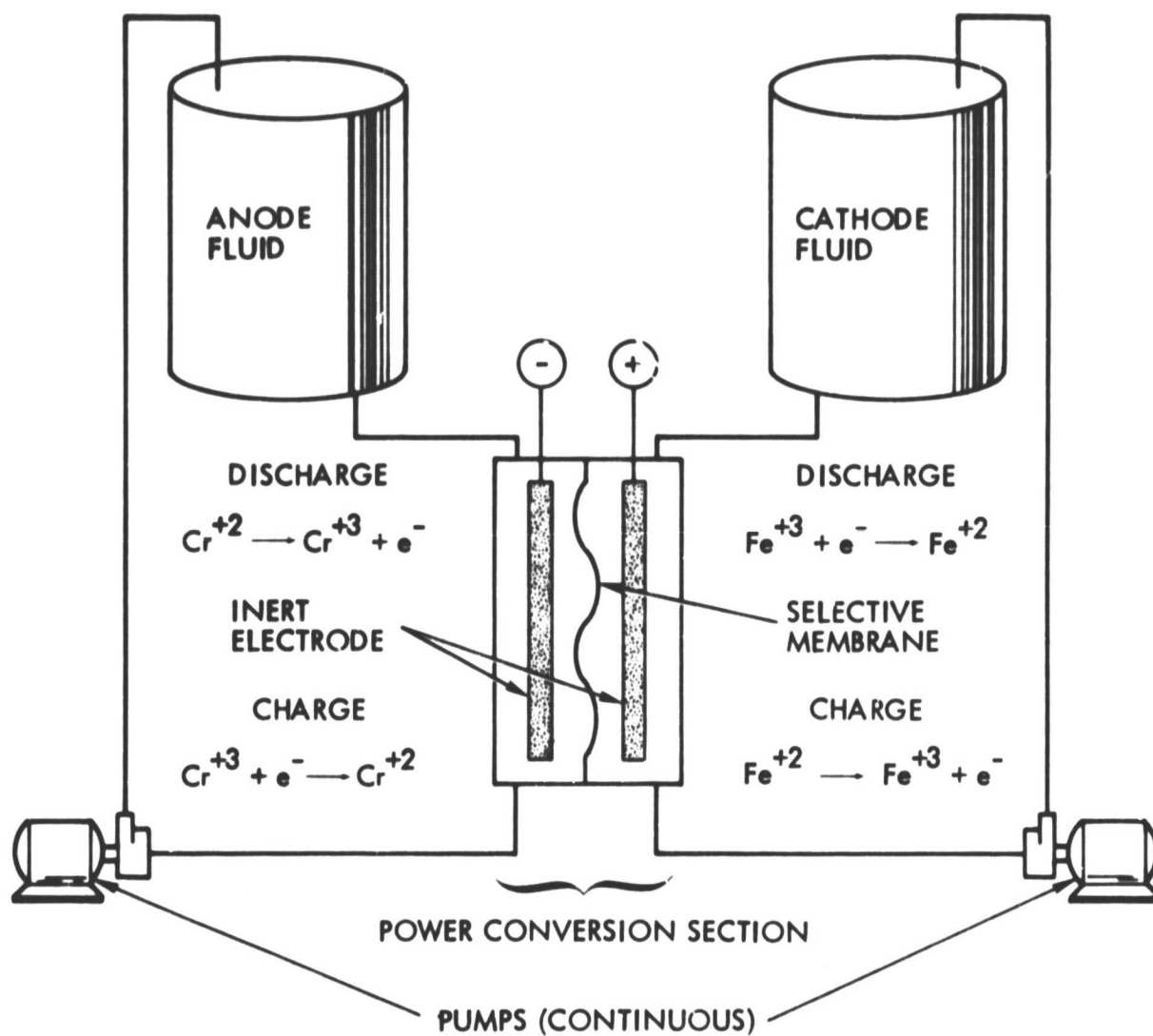
The cathode compartment of the rebalance cell contains ferric ions which are reduced at an inert electrode according to the following reaction:



The overall reaction in the rebalance cell is then:



*Reference 25.



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Figure 6-4. Iron-Chromium Redox System (LeRC)

evolved and pose a safety problem. Second, it maintains a constant balance in the ratio of $\text{Cr}^{+2}/\text{Cr}^{+3}$ and $\text{Fe}^{+3}/\text{Fe}^{+2}$ at all times which is essential for long-term operation.

Normal discharge voltage for this system is 0.90 volts per cell. Overall discharge voltage is maintained at an essentially constant level throughout the discharge period with the use of trim cells. Nominal charge voltage for this system is 1.25 volts per cell. Overall charge voltage is again maintained at an essentially constant level throughout the charge period with the use of trim cells.

One area of concern with this system is that maximum stack voltage is limited to about 100 volts. Beyond this level shunt currents tend to increase through the parallel-connected electrolyte paths and current efficiency is diminished. Another area of concern is ultimate life of the membrane.

Areas which had been of concern until recently were hydrogen evolution at the anode during charge and cross diffusion of active species across the membrane. The hydrogen evolution problem has been greatly diminished by use of an anode catalyst. What little hydrogen that is evolved is consumed in the rebalance cell. The cross-diffusion problem has been greatly diminished by use of improved ion-selective membranes. Cross-diffusion rates have been reduced to the point where it would take 40 years before cross diffusion would render the system inoperative.

A sizable program is underway at NASA LeRC to develop this system for load-leveling applications. Five cell stacks with 306 cm^2 area were run at levels of 54 mWe/cm^2 . Functionality was demonstrated for the trim cells, the open-circuit cells, and the rebalance cells. Several 1-2 kWe demonstration units are planned for development and test during 1979. A 10 kW unit is to be in operation by FY83 and a 1 MW unit is planned for installation in the BEST facility in FY86. FY80 funding is about \$1 M. Funding is expected to increase to \$2 to \$5 M by FY83.

Projected cost of the electrochemical system is \$132/ kWe + \$22/ kWeh . The former is associated with the cost of the cell stack or power conversion section and the latter is associated with the cost of the storage tanks and electrolyte solutions. Round-trip energy efficiency is approximately 75%. Cycle life during its anticipated 40-year operational life is expected to be 10,000 cycles. If an increased level of funding is provided, it is anticipated that the system will be available by 1990.

D. IRON-IRON REDOX SYSTEM -- GEL CO.*

A schematic diagram of Gel Co.'s iron-iron redox system is given in Figure 6-5. Also shown are the electrochemical reactions that take

*Reference 26.

place within the system during charge and discharge. The system is similar to the LeRC redox system except that one of its electrode reactions involves the deposition and dissolution of a solid active material during charge and discharge, respectively. This occurs in the anode compartment where metallic iron is plated out during charge and goes into solution as ferrous ions upon discharge. In the cathode compartment ferrous ions are oxidized to ferric ions during charge and ferric ions are reduced to ferrous ions upon discharge at an inert electrode. The two compartments are separated by a microporous barrier. This barrier is not an ion-selective membrane as in the LeRC system, but merely a porous physical separator. As such, the barrier does not entirely stop cross diffusion of reactants but merely impedes the transport of these species between compartments. In a practical battery the cells are connected electrically in series while electrolytes are transported into and out of their respective compartments in a parallel-flow manner.

Nominal discharge voltage for this system is 0.8 volts per cell and is relatively constant throughout the discharge period. Nominal charge voltage for this system is 1.2 volts per cell and is relatively constant through the charge period.

There are several areas of concern with this particular redox system. One of these is that it evolves appreciable amounts of hydrogen at the iron anode during charge. This hydrogen is not consumed as in the case of the LeRC system, so it must be vented and thereby poses a safety problem. Next, the system has appreciable amounts of cross diffusion whereby the ferric ions can cross over from the cathode to the anode compartment and react chemically with the metallic iron. This phenomenon is in essence a self-discharge reaction and reduces overall efficiency. Next this system, like the LeRC system, is limited in total stack voltage due to the parallel electrolyte flow paths and consequent shunt currents. The maximum stack voltage has not been specified at this time. Finally, the system requires very high flow rates of electrolyte to maintain even modest current densities. This in turn will require high pumping power requirements which will diminish overall efficiency.

A small program is underway at Gel Co. to improve performance of their system. Funding is at a level of \$125K per year and about five personnel are involved in the program. A single cell with 387 cm² area was operated for 1000 cycles and a multiplate cell was operated for 500 cycles without apparent degradation. Gel Co. started to design a 5 kWe, 100 kWh storage system for a photovoltaic demonstration plant in 1978. The program was delayed, however, for two years.

Gel Co.'s projected cost in large-scale production is almost only \$3/kWh. They attribute this to use of low-cost materials (inexpensive carbon-plastic composite frames and iron solutions)

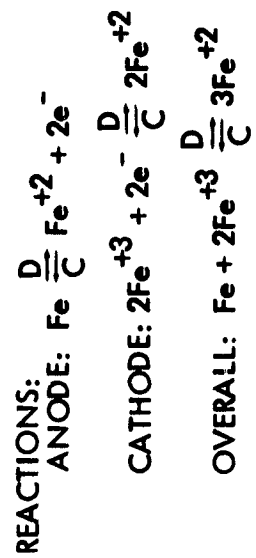


Figure 6-5. Iron-Iron Redox System (Gel. Co.)

and the lack of need for expensive ion-selective membrane separators. Gel Co.'s projected energy efficiency is 60% to 64%. No estimates of cycle life have been given at this time.

The above cost projections were reviewed within the past year by DOE/NASA and are considered optimistic. The efficiency projection was also reviewed by DOE/NASA and in their judgment these projections are optimistic. In addition, DOE/NASA was concerned with inherent limitations in performance aspects of the system.

In view of the above, no reliable estimates can be made on cost, performance, and availability of Gel Co.'s redox system at this time.

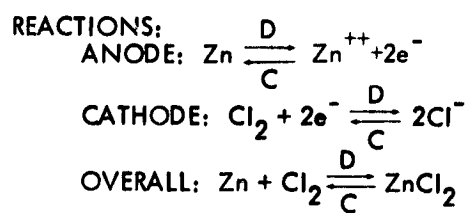
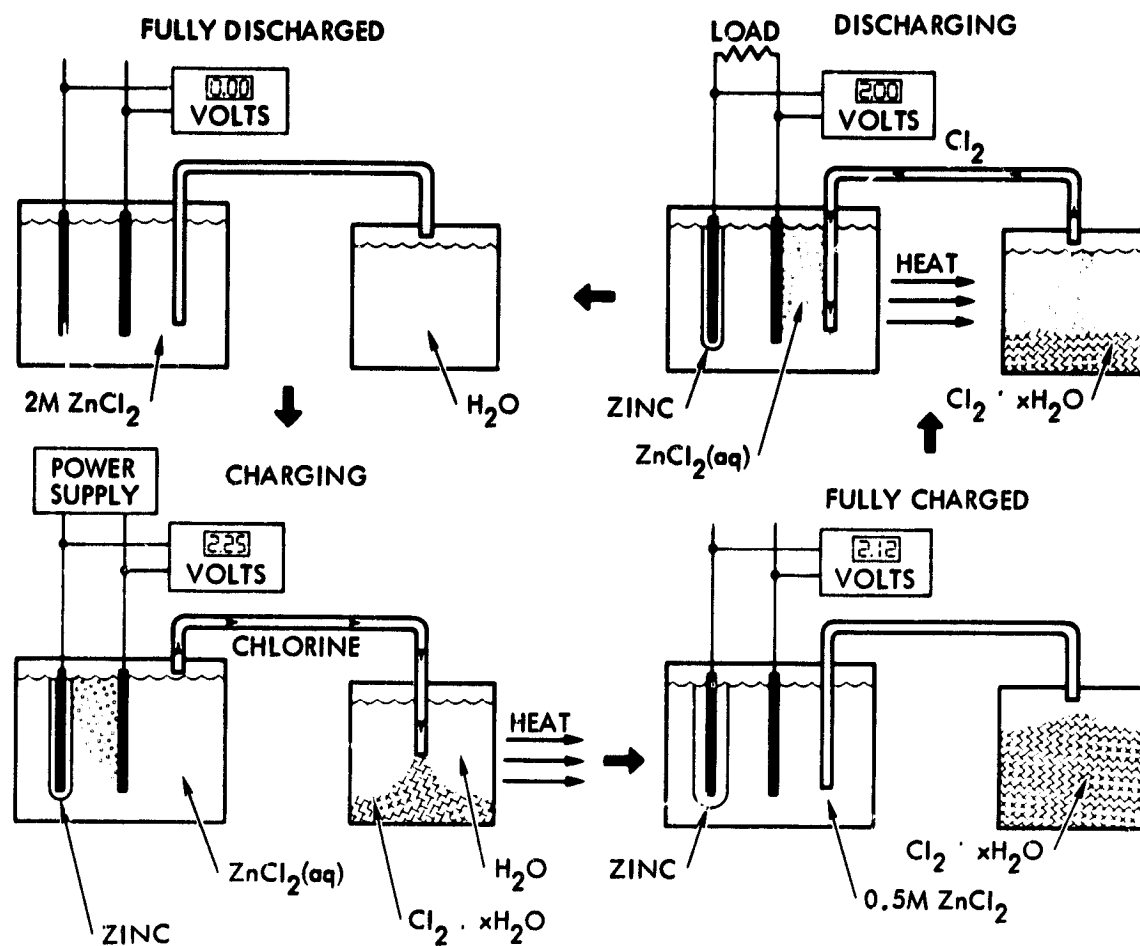
E. ZINC-CHLORINE SYSTEM -- ENERGY DEVELOPMENT ASSOCIATES'*

A schematic diagram of Energy Development Associates'(EDA) zinc-chlorine system is given in Figure 6-6. Also shown are the electrochemical reactions that take place within the system during charge and discharge. The system is comprised basically of a cell stack with zinc and chlorine electrodes and an external storage tank for chlorine which is stored as a hydrate. In the fully discharged state, the external tank is filled with water and the stack contains zinc-chloride electrolyte. During charge, zinc is deposited on the anode and chlorine gas is evolved at the cathode. The chlorine gas is transferred to the storage tank which is cooled to 5°C to form the hydrate. During discharge, the heat generated in the stack is used to warm the tank and decompose the hydrate into chlorine gas. The chlorine gas is then returned to the cathode, where it is reduced in the discharge process. The cells in the stack are connected electrically in series, while the electrolyte is transported into and out of each cell in a parallel-flow manner.

Nominal discharge voltage is 1.95 volts per cell. End of discharge voltage is 1.6 to 1.7 volts per cell. Nominal charge voltage is 2.13 volts per cell. End of charge voltage is 2.25 volts per cell.

There are some areas of concern with this system. One of these is that some hydrogen is evolved from the anode, especially during charge. Without adequate ventilation, this hydrogen would pose a safety threat. Another concern is the requirement that the zinc be stripped completely from the anode during and after discharge to avoid the problem of dendrite growth. Originally, this process was done electrochemically by forcing the system into reversal after each discharge. Recently, it has been decided that the stripping can be accomplished more readily by passing chlorine solution over the incompletely stripped electrode and chemically dissolving the residual

*Reference 27.



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Figure 6-6. Zinc-Chlorine System (EDA)

zinc. This stripping process requires about one hour for completion. Another concern is that charge must start at 0.0 volts at full charge current for a few seconds until voltage builds up to nominal charge voltage. This requirement necessitates the use of specially designed charging equipment. A final area of concern is that maximum stack voltage is limited to 21 volts. Beyond this level, shunt currents tend to increase through the parallel electrolyte paths and current efficiency is diminished.

A sizeable program is underway at EDA to develop this system for load-leveling applications. Funding is at a level near \$5M per year. The company has developed and is now testing 45 kWeh modules (15 kWe for 3 hrs). Each module delivers 21 volts and is equipped with its own auxiliaries (refrigeration, hydrate storage tank, pumps, etc.). The company is planning a demonstration of their system in the BEST facility in the first quarter of 1981. This will be a 5 MWeh system (1 MWe for 5 hrs).

Projected cost of the system is \$59/kWe + \$27/kWeh. The former is associated with the cost of the cell stack while the latter is associated with the cost of the hydrate storage system. Round-trip energy efficiency is in the range of 71% to 74%. Projected cycle life is in the range of 2500 to 3500 cycles. Pending continuance of existing funding levels, it is anticipated that the system will be available by 1985.

F. LITHIUM METAL-IRON SULFIDE SYSTEM -- ARGONNE NATIONAL LABORATORY*

Schematic diagrams of lithium metal-iron sulfide systems are given in Figures 6-7 and 6-8, which also show the electrochemical reactions that take place within the systems during charge and discharge. The cells are hermetically sealed and operate in the elevated temperature range of 400° to 475°C. Electrolyte for these cells is a molten salt comprised of a LiCl-KCl eutectic mixture with a melting point of 352°C. The anodes are solid lithium alloy sheets comprised of either lithium and aluminum or lithium and silicon. The cathodes are comprised of solid iron sulfide, FeS, and a suitable current collector. Separators are comprised of either boron nitride fabric or porous ceramic materials such as MgO.

Nominal discharge voltage for these cells is in the range of 1.2 to 1.3 volts per cell. End of discharge voltage is 1.0 volts per cell. Nominal charge voltage is 1.5 to 1.6 volts per cell. End of charge voltage is in the range of 1.6 to 2.0 volts per cell.

There are three areas of concern with the lithium metal-iron sulfide cells. One of these is corrosion of the positive current collector by the iron sulfide. Another is the electrical conductivity

*References 28, 29.

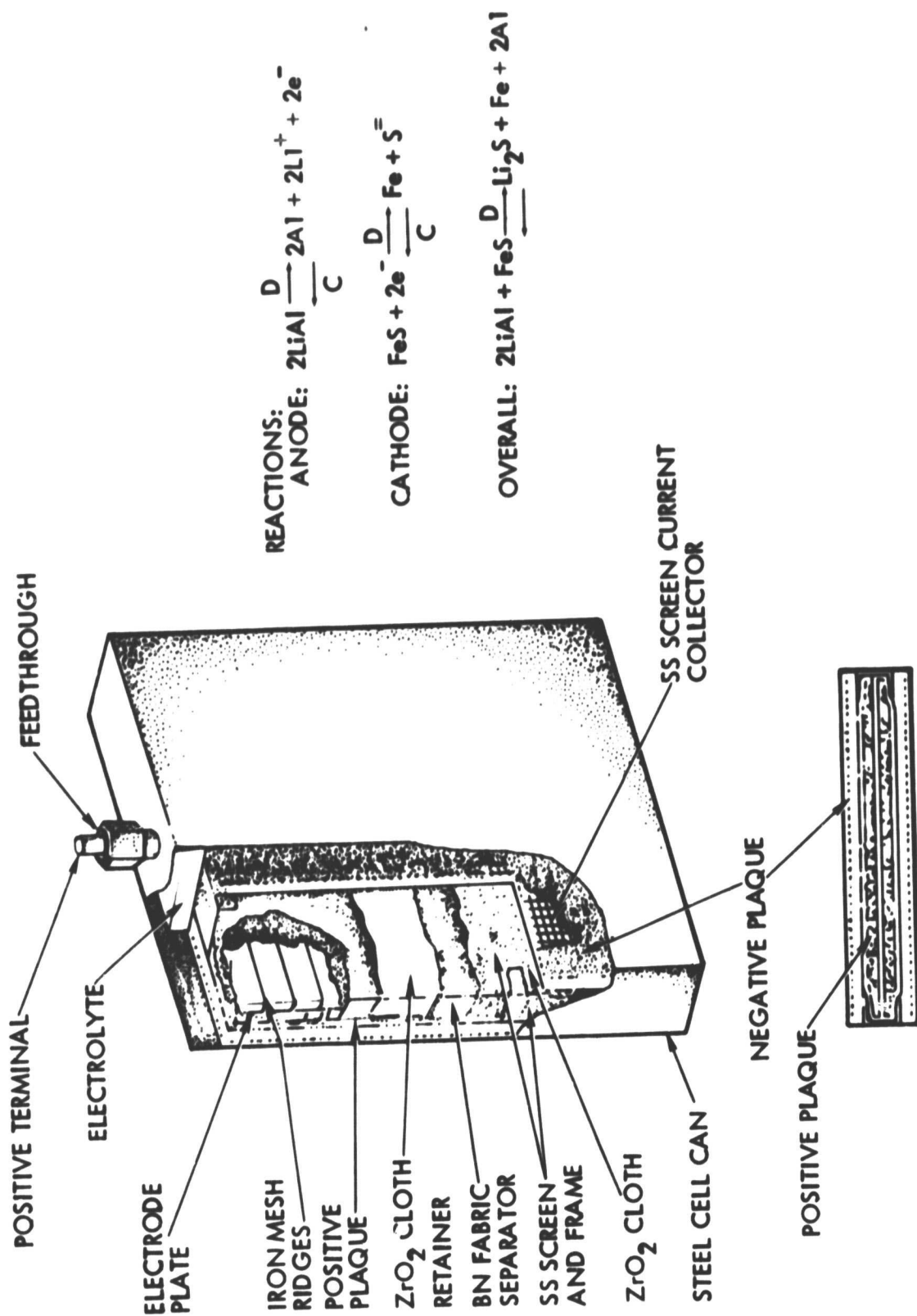


Figure 6-7. Lithium Aluminum-Iron Sulfide System
(Argonne National Laboratory)

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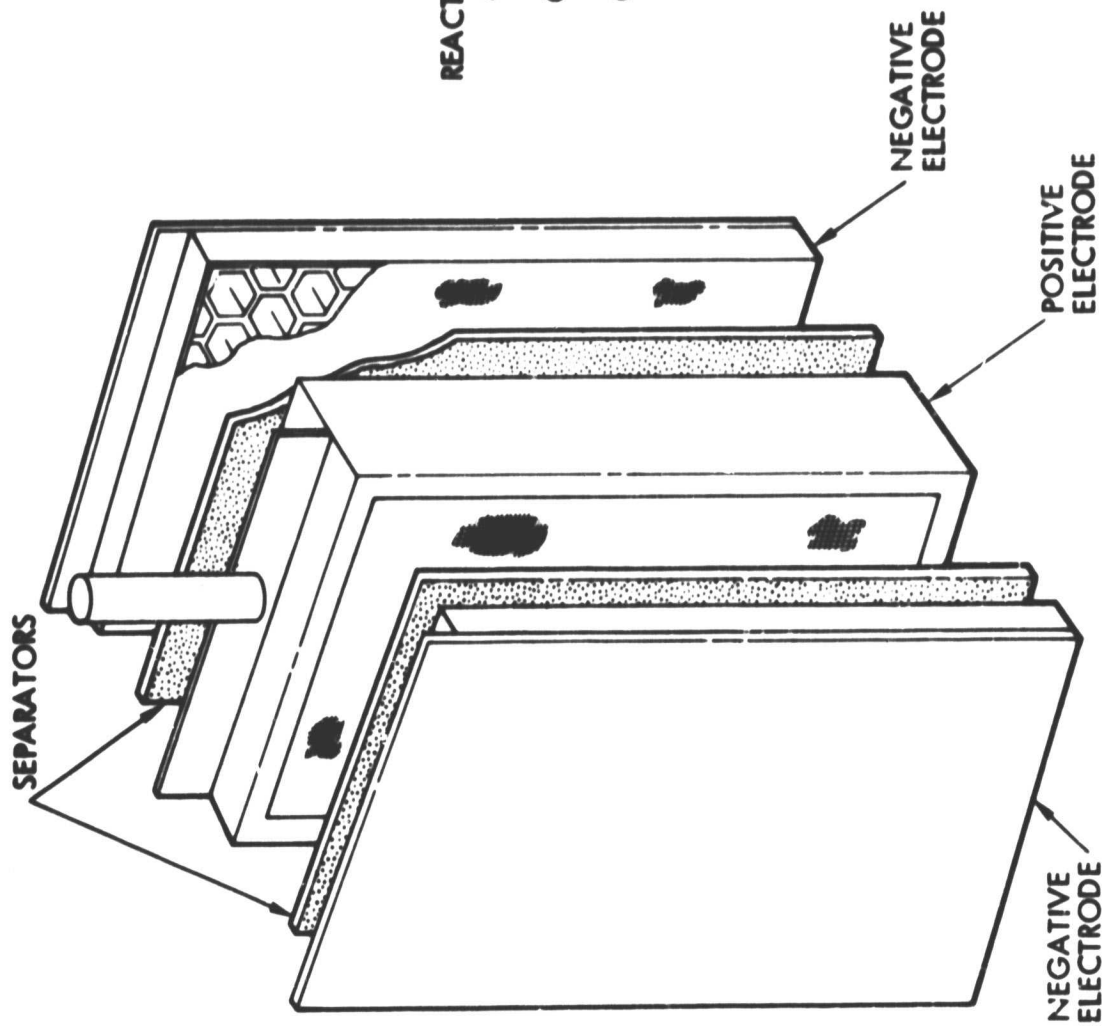
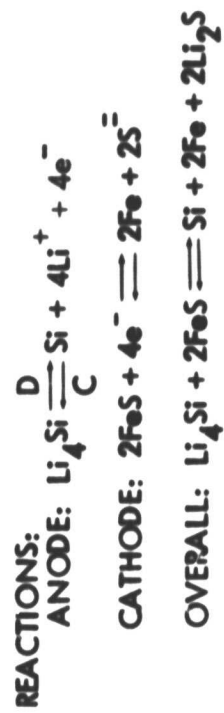


Figure 6-8. Lithium Silicon-Iron Sulfide System
(Atomics International)

of the positive active material. The other is the life of both the positive and negative electrodes.

A substantial program is underway at Argonne National Laboratory to develop these systems for electric vehicle propulsion and also for load-leveling applications. Funding is at a level of about \$5.4M per year; of this, approximately one-half is directed to contracted agencies. Major contractors are Eagle Picher, Gould, and Atomics International. Most of the funding at the present time is allocated to the area of electric vehicle propulsion with Eagle Picher and Gould. The remainder is allocated to the area of load leveling with Atomics International. Small cells of 100 Weh size have been operated for 700 to 1000 cycles. A search is underway to replace the relatively expensive ceramic power separators. System design studies are being carried out for large storage plants based on this type of battery. An electric vehicle demonstration with this battery is scheduled for March, 1979. This will involve a 40 kWh unit in a Volkswagon Van.

Projected cost of lithium metal-iron sulfide battery modules is \$54/kWh. Round-trip energy efficiency is estimated to be 85%. Cycle life is expected to be 3000 cycles at 85% DOD. Pending continuance of existing funding levels, it is anticipated that the system will be available by 1990.

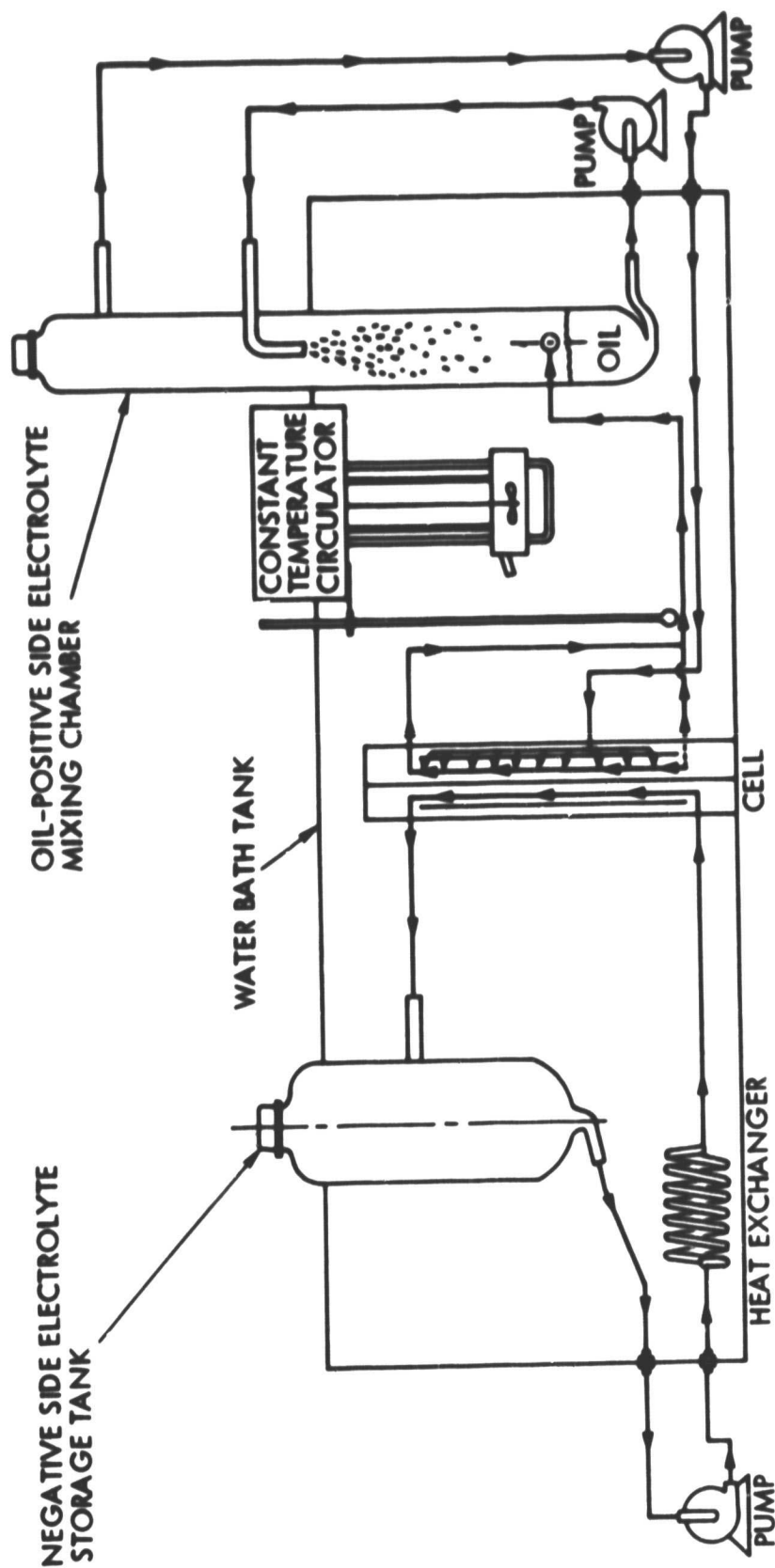
G. ZINC-BROMINE SYSTEM

1. Gould*

A schematic diagram of Gould's zinc-bromine system is given in Figure 6-9, which also shows the electrochemical reactions that take place within the system during charge and discharge. The system operates at ambient or slightly above ambient temperatures. During charge, zinc is plated on the anode and bromine is evolved at the cathode. The evolved bromine is transferred to an external chamber where it is mixed and stored with an organic liquid complexing oil. During discharge, the zinc is oxidized at the anode and the complexed bromine is reduced at the cathode. Porous titanium is the material of construction for both electrodes. The bromine cathode contains a catalyst for bromine reduction during discharge. A porous material is used to separate the anode and cathode compartments. This material is a physical-type separator and not an ion-selective membrane.

Voltage of the system remains relatively constant during both charge and discharge. Nominal discharge voltage is 1.60 volts per cell and nominal charge voltage is 1.95 volts per cell.

*Reference 30.



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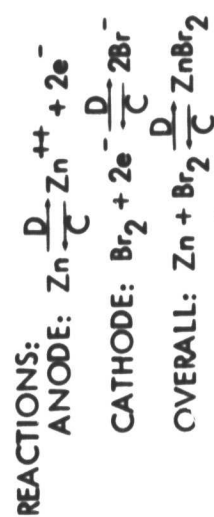


Figure 6-9. Zinc-Bromine System (Gould)

There are three areas of concern with this system. First, the system is limited in stack voltage due to shunt currents through the parallel-connected electrolyte paths. Maximum stack voltage has not been established at this time. Second, the use of relatively expensive titanium for the electrodes contributes to increased materials costs. Third, the use of expensive ruthenium catalyst for bromine also contributes to increased materials cost.

A limited program is underway at Gould to develop this system for load-leveling applications. The total number of personnel involved is ten, and the funding level is about \$600K per year. Gould demonstrated over 2000 cycles on a small single cell in the laboratory. They now have a 1 kWeh unit undergoing test in the laboratory. During 1979 the company will develop and test an 8 kWeh demonstration unit. In addition, the company is studying design aspects of large-scale, zinc-bromine storage systems.

Projected cost of the Gould zinc-bromine battery modules is \$49 to \$59/kWeh. Round-trip energy efficiency is estimated to be 70%. Cycle life is expected to be 2500 cycles at 80% DOD. Pending continuance of funding it is anticipated that the system will be available by 1990.

2. Exxon*

A schematic diagram of Exxon's zinc-bromine system is given in Figure 6-10, which also shows the electrochemical reactions that take place during charge and discharge. The system operates at ambient or slightly above ambient temperatures. The system is similar to that of Gould, in that it employs an organic complexing agent to store the bromine. One major difference is that Exxon employs a cation exchange membrane to separate the anode and cathode compartments. Zinc ions are transported across the membrane to maintain charge neutrality. Use of this membrane prevents transport of bromine to the zinc anode where chemical reaction between zinc and bromine could take place and result in low current efficiency. Another major difference is that Exxon employs inexpensive conductive plastic composite electrodes in place of porous titanium electrodes.

Voltage of the system remains relatively constant during both charge and discharge. Nominal discharge voltage is 1.6 volts per cell and nominal charge voltage is 1.8 volts per cell.

There are two areas of concern with this system. First, the system is limited in stack voltage due to shunt currents through the parallel-connected electrolyte paths. Maximum stack voltage has not been specified at this time. Second, the life of the cation selective membrane is of concern over the long term.

*Reference 31.

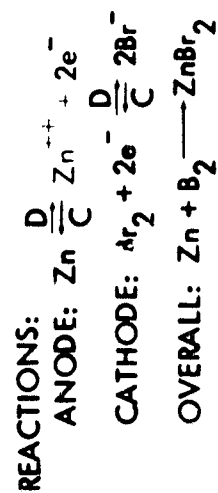
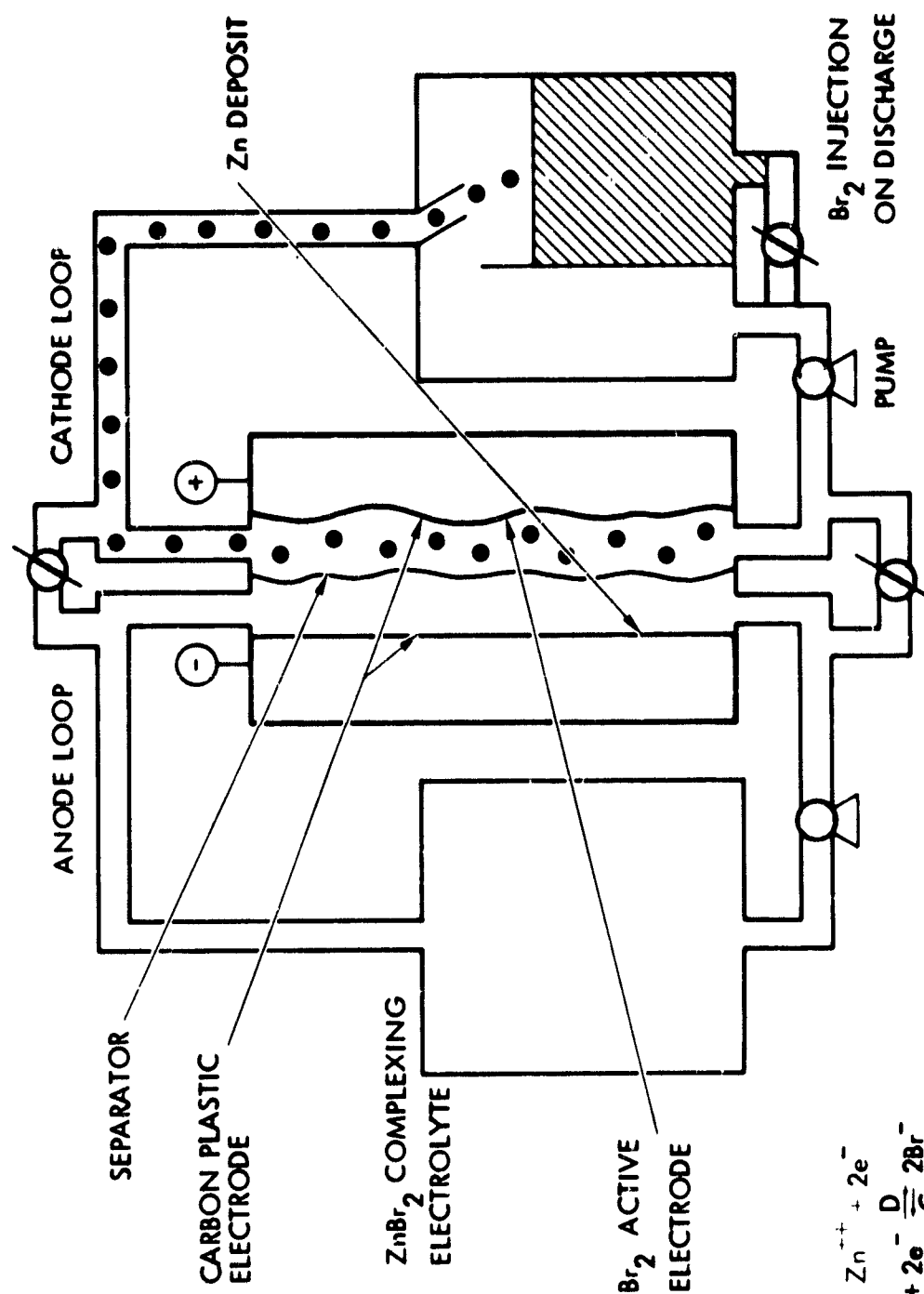


Figure 6-10. Zinc-Bromine System (Exxon)

A substantial internal program is underway at Exxon to develop this system for load leveling and also for electric vehicle propulsion applications. Exxon management does not wish to disclose the level of effort at this time. The company has developed a 1 kWe unit and has tested it in the laboratory. To date the unit has been operated for 100 cycles with no signs of degradation in performance. Two or three kWe units are to be built and placed on test during 1979. In addition, the company has been studying the design aspects of large-scale, zinc-bromine storage plants.

Projected cost of the Exxon zinc-bromine system is \$32/kWeh. Round-trip energy efficiency is estimated to be 80%. Cycle life is expected to be in the range of 2500 to 5000 cycles at 80% DOD. Pending continuance of adequate funding levels, it is anticipated that the system will be available by 1990.

3. General Electric*

A schematic diagram of General Electric's zinc-bromine system is shown in Figure 6-11, which also shows the electrochemical reactions that take place within the system during charge and discharge. The system operates at ambient or slightly above ambient temperatures. The General Electric zinc-bromine system differs from those of Gould and Exxon, in that it does not employ a complexing agent for the bromine. The bromine is stored as a liquid under pressure in an external tank. The system employs a cation permeable membrane to separate the anode and cathode compartments. This membrane is DuPont's "Nafion" which is the same employed in General Electric's H₂-O₂ fuel cell. Zinc ions, as well as lithium and potassium ions which are present in the mixed electrolyte, are transported across the membrane to maintain charge neutrality. The membrane inhibits the transport of bromine to the zinc anode where chemical reaction between zinc and bromine could take place and result in low current efficiency. Carbon substrates are employed for both the zinc and bromine electrodes.

Nominal discharge voltage for this system is 1.6 volts per cell. End of discharge voltage is 1.5 volts per cell. Nominal charge voltage is 1.8 volts per cell. End of charge voltage is 2.1 volts per cell.

There are four major areas of concern with the General Electric zinc-bromine system. The first is whether container materials can withstand the corrosive nature of bromine over the long term. The second is the stability of the cation selective membrane over the long term. The third is cost reduction of the relatively expensive membrane. The fourth concern is the maximum stack voltage due to shunt currents, as previously discussed.

*Reference 32.

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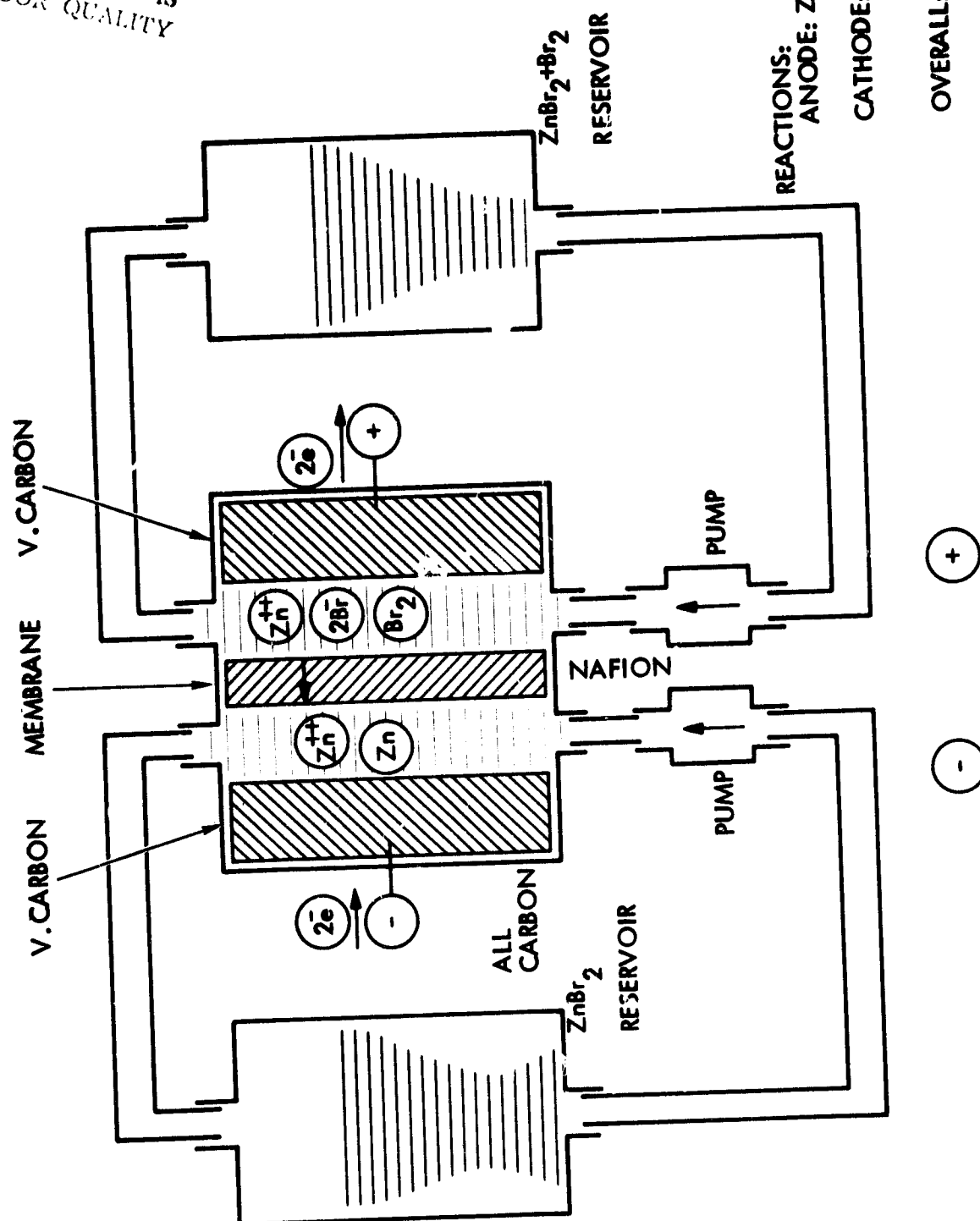


Figure 6-11. Zinc-Bromine System (General Electric)

A small program was underway at General Electric to develop this system for load-leveling applications. The company demonstrated 2000 cycles on a small 4 cm² cell in the laboratory. Also, the company demonstrated 170 cycles on a larger 125 cm² cell when a pump became inoperative. The cell had not degraded in performance to this point. Finally, the company developed a 1000 cm² cell and was about to begin testing it, when the program was terminated by management in 1978 for non-technical reasons. It has not been decided whether the program will be reactivated.

While the program was active the company also carried out cost and performance projections for large-scale versions of their system. Projected cost was \$58/kWeh. Round-trip energy efficiency was estimated to be 75%. Cycle life was expected to be at least 2000 cycle at 80% DOD. No projections on availability can be made until it is decided whether the program will be continued.

H. IRON-AIR SYSTEM -- WESTINGHOUSE*

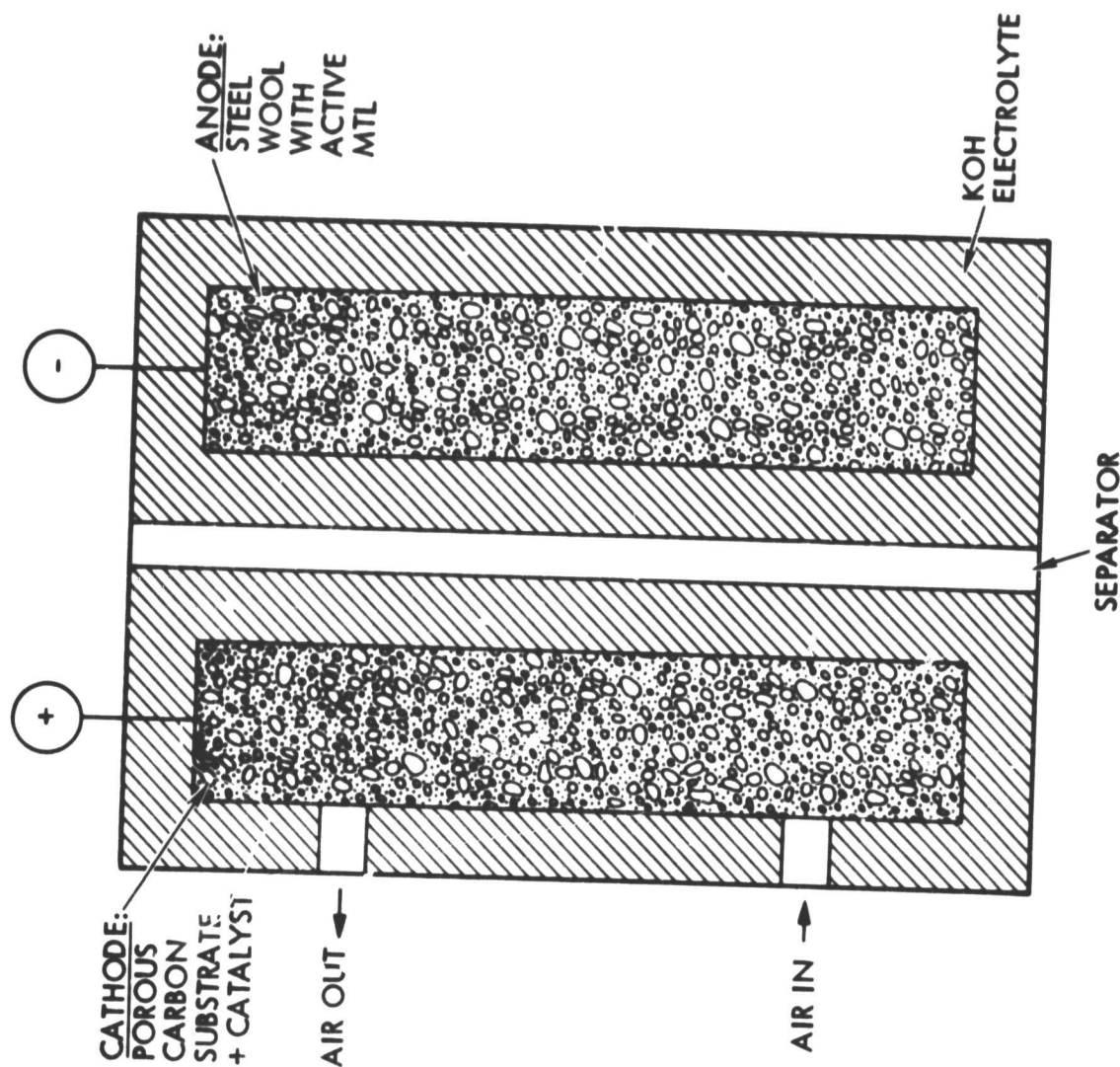
A schematic diagram of Westinghouse's iron-air system is given in Figure 6-12, which also shows the electrochemical reactions that take place within the system during charge and discharge. The system operates at ambient or slightly above ambient temperatures. The system is classified as an alkaline-type battery because it employs potassium hydroxide as electrolyte. The anode is comprised of a steel wool substrate with active iron material. The air cathode is comprised of a porous carbon substrate with dispersed catalyst to activate the oxygen. All materials of construction are very low cost. Very small amounts of silver are used as the air electrode catalyst, and total catalyst cost is quite low.

Nominal discharge voltage for this system is 0.8 volts per cell. End of discharge voltage is 0.6 volts per cell. Nominal charge voltage is 1.5 volts per cell. End of charge voltage is 1.8 volts per cell.

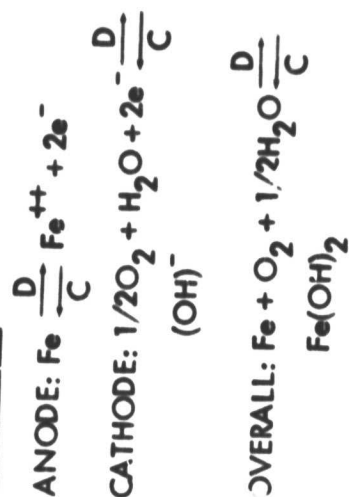
There are three major areas of concern with this system. The first is substantial polarization at the air electrode during both charge and discharge. This results in relatively low voltage, and hence energy efficiency. The second is the life of the air electrode over the long term. The third is the appreciable amount of hydrogen evolution at the iron anode during charge. The hydrogen must be vented, and this poses a safety problem in the absence of adequate ventilation.

A modest program is underway at Westinghouse to develop this system for electric vehicle propulsion. Funding is at a level of about \$450K per year and the number of personnel involved is nine.

*Reference 33.



REACTIONS



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Figure 6-12. Iron-Air System (Westinghouse)

The company demonstrated 300 cycles to date on laboratory size cells, each with an area of 40 cm². They are scaling up to full size cells with areas of 400 cm² each during 1979. They expect to have units available for electric vehicle propulsion by December 1980. They are continuing research on air electrode catalysts and improved cathode configurations to reduce polarization at the air electrode.

Projected cost the Westinghouse iron-air system is \$32/kWeh. Round-trip energy efficiency is estimated to be 50%. Cycle life is expected to be 1000 cycles at 80% DOD. Pending continuance of adequate funding, the system should be available by 1985.

I. NICKEL-IRON SYSTEM

1. Westinghouse*

A schematic diagram of Westinghouse's nickel-iron system is given in Figure 6-13, which also shows the electrochemical reactions that take place within the system during charge and discharge. The system operates at ambient or slightly above ambient temperatures. The system is classified as an alkaline-type battery because it employs potassium hydroxide as electrolyte. The anode is comprised of a steel wool substrate with active iron material. The cathode is comprised of a nickel-plated steel wool substrate with active nickel material.

Nominal discharge voltage for this system is 1.2 volts per cell. End of discharge voltage is 1.0 volts per cell. Nominal charge voltage is 1.6 volts per cell. End of charge voltage is 1.7 volts per cell.

There are two major areas of concern with this system. The first is the high cost of nickel employed in the cathode. The second is the appreciable amount of hydrogen evolution at the iron anode during charge. The hydrogen must be vented, and this poses a safety threat in the absence of adequate ventilation.

A sizeable program is underway at Westinghouse to develop this system for electric vehicle propulsion. Funding is at a level of about \$2M per year and 20 personnel are involved. The company previously built a 106 kWeh unit for a mining application. They are currently in the process of developing full size, 250 AH cells for electric vehicles. The company is planning to develop a 25 kWeh unit for an electric vehicle demonstration at an undisclosed date.

Projected cost of the Westinghouse nickel-iron system is \$54/kWeh. Round-trip energy efficiency is estimated to be 60%. Cycle life is expected to be 2000 cycles. Pending continuance of adequate funding levels, the system should be available by 1990.

*Reference 34.

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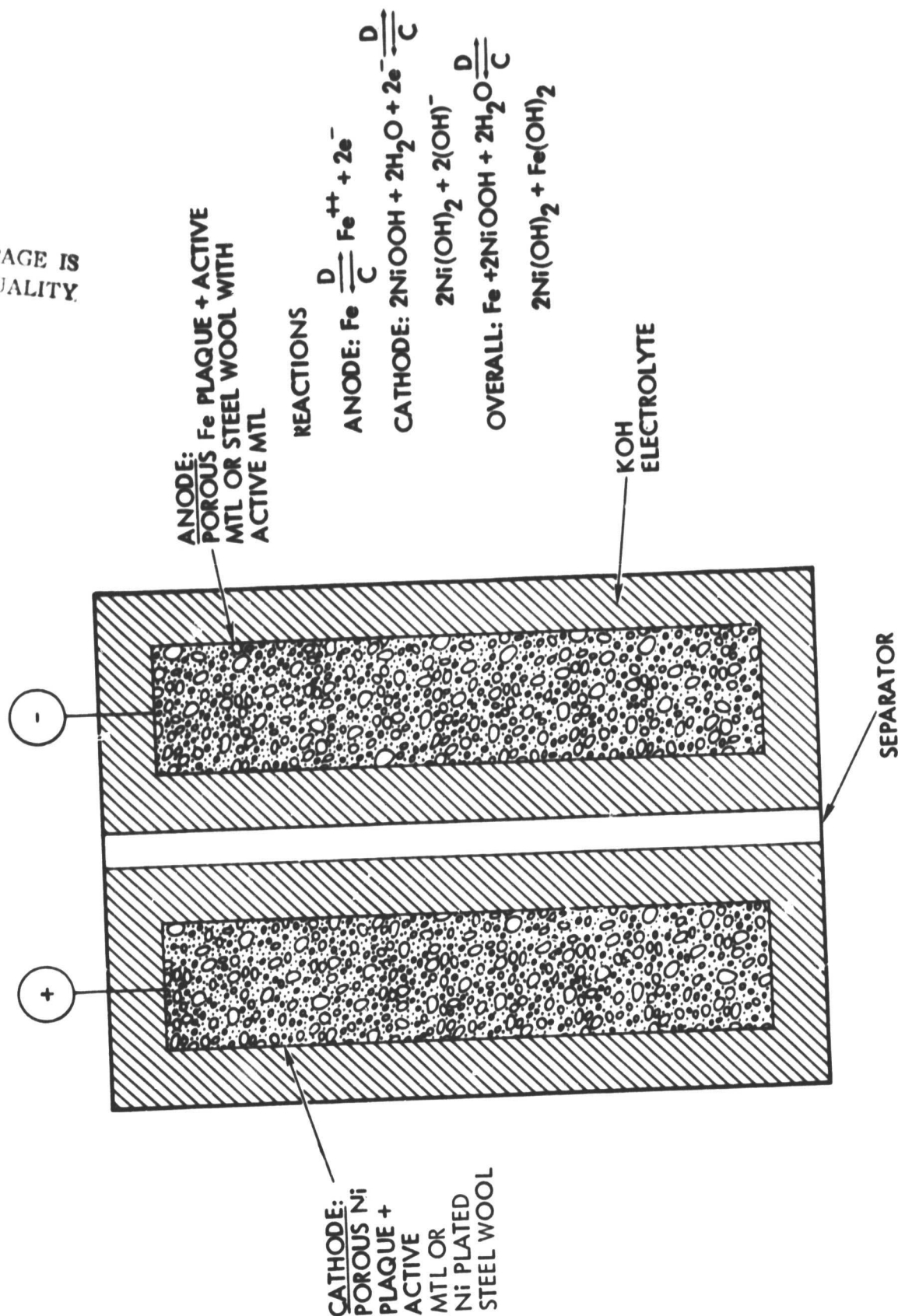


Figure 6-13. Nickel-Iron System (Westinghouse and Eagle Picher)

2. Eagle Picher*

A schematic diagram of Eagle Picher's nickel-iron system is given in Figure 6-13, which also shows the electrochemical reactions that take place within the system during charge and discharge. The system operates at ambient or slightly above ambient temperature. The system is classified as an alkaline-type battery because it employs potassium hydroxide as electrolyte. The system is essentially the same as the Westinghouse system except in regard to electrode configuration. The iron anode is comprised of a sintered, porous iron structure. This anode is being specially developed for Eagle Picher by the Swedish National Development Company. The cathode is comprised of a porous nickel plaque impregnated with active nickel material. The cathode is similar to that employed in aerospace nickel-cadmium cells. Unit cell voltages are the same as for the Westinghouse nickel-iron system.

Areas of concern are also the same as for the Westinghouse system. There is the high cost of nickel and hydrogen evolution. The cost is a greater problem with the Eagle Picher system, in that it contains appreciable amounts of nickel in its positive substrate, in addition to the nickel in the active nickel material.

A sizeable program is underway at Eagle Picher to develop the system for electric vehicle propulsion. Funding is at a level of about \$850K per year and 20 personnel are involved. During 1978, the company completed development of the first group of sub-scale 100 AH cells. These were placed on cycle test and have completed a few hundred cycles to date in early 1979. During 1979, the company will be scaling up to the full size required for electric vehicles. Demonstration of a 25 kWh battery in an electric vehicle is planned for the near future.

Projected cost of the Eagle Picher nickel-iron system is \$65/kWh. Round-trip energy efficiency is estimated to be between 65% and 70%. Cycle life is expected to be 2000 cycles at 80% DOD. Pending continuance of adequate funding, the system should be available by 1990.

J. NICKEL-HYDROGEN SYSTEM -- ERC**

A schematic diagram of one configuration of a nickel-hydrogen system is given in Figure 6-14, which also shows the electrochemical reactions that take place within the system during charge and discharge. The particular configuration shown in Figure 14 consists of a series-connected cell stack inside a pressure vessel that contains the hydrogen. Hydrogen is distributed to the cells through a common manifold system. Another configuration consists of individual

*Reference 35.

**Reference 36.

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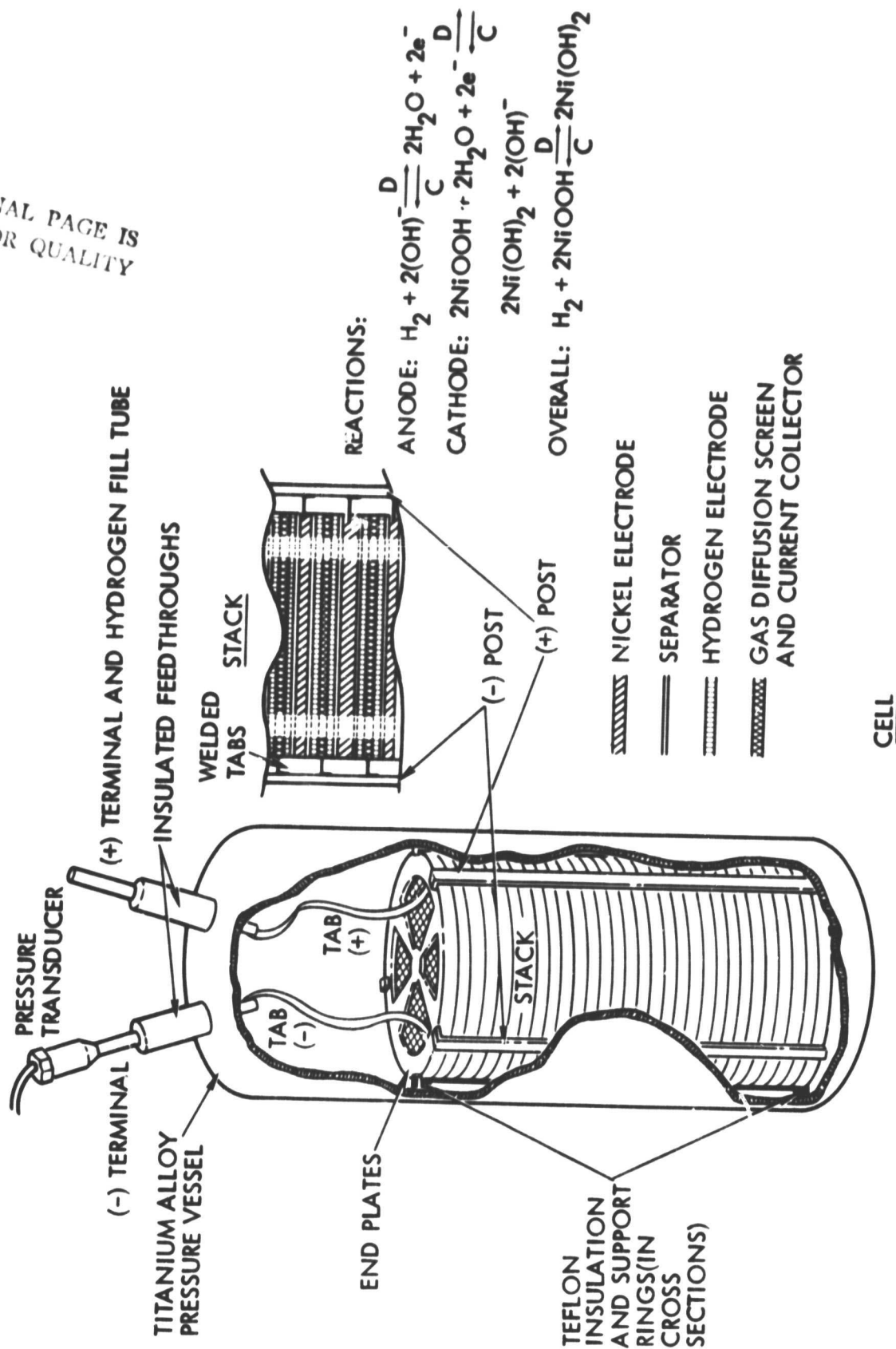


Figure 6-14. Nickel-Hydrogen System (ERC)

cells each with its own pressure vessel to contain the hydrogen. In either case, the system is classified as an alkaline-type battery because it employs potassium hydroxide as electrolyte. The system operates at ambient or slightly above ambient temperatures. The hydrogen anode is comprised of a catalyzed porous nickel plaque. The cathode may be either the sintered or pressed type. The sintered type is comprised of a sintered, porous nickel plaque impregnated with active nickel material. The pressed type is comprised of active nickel material pressed onto a nickel screen. During charge, hydrogen is evolved and accumulates inside the pressure vessel. Charge is terminated when hydrogen pressure reaches 500 to 600 psig. During discharge, hydrogen is consumed by the cells and pressure declines. Discharge is terminated when pressure reaches about 100 psig. The hydrogen pressure then gives an indication of the state of charge.

Nominal discharge voltage for this system is 1.2 volts per cell. End of discharge voltage is 1.0 volts per cell. Nominal charge voltage is 1.5 volts per cell. End of charge voltage is 1.6 volts per cell.

One area of concern is the existence of high pressure hydrogen and the possibility of leaks. This could pose a safety threat in the absence of adequate ventilation. Another area of concern is the use of costly nickel.

The United States Air Force and Navy and Comsat are sponsoring sizeable programs to develop and qualify the nickel-hydrogen system for use in aerospace power systems. The major incentive for this effort is that the nickel-hydrogen system offers higher energy density and longer cycle life than the currently employed nickel-cadmium system. Organizations involved in the development are Hughes, Comsat, Energy Research Company, and Eagle Picher. The Navy is currently using a 30 AH-28 volt system in a satellite. The Air Force tested a 50 AH-28 volt system on another satellite.

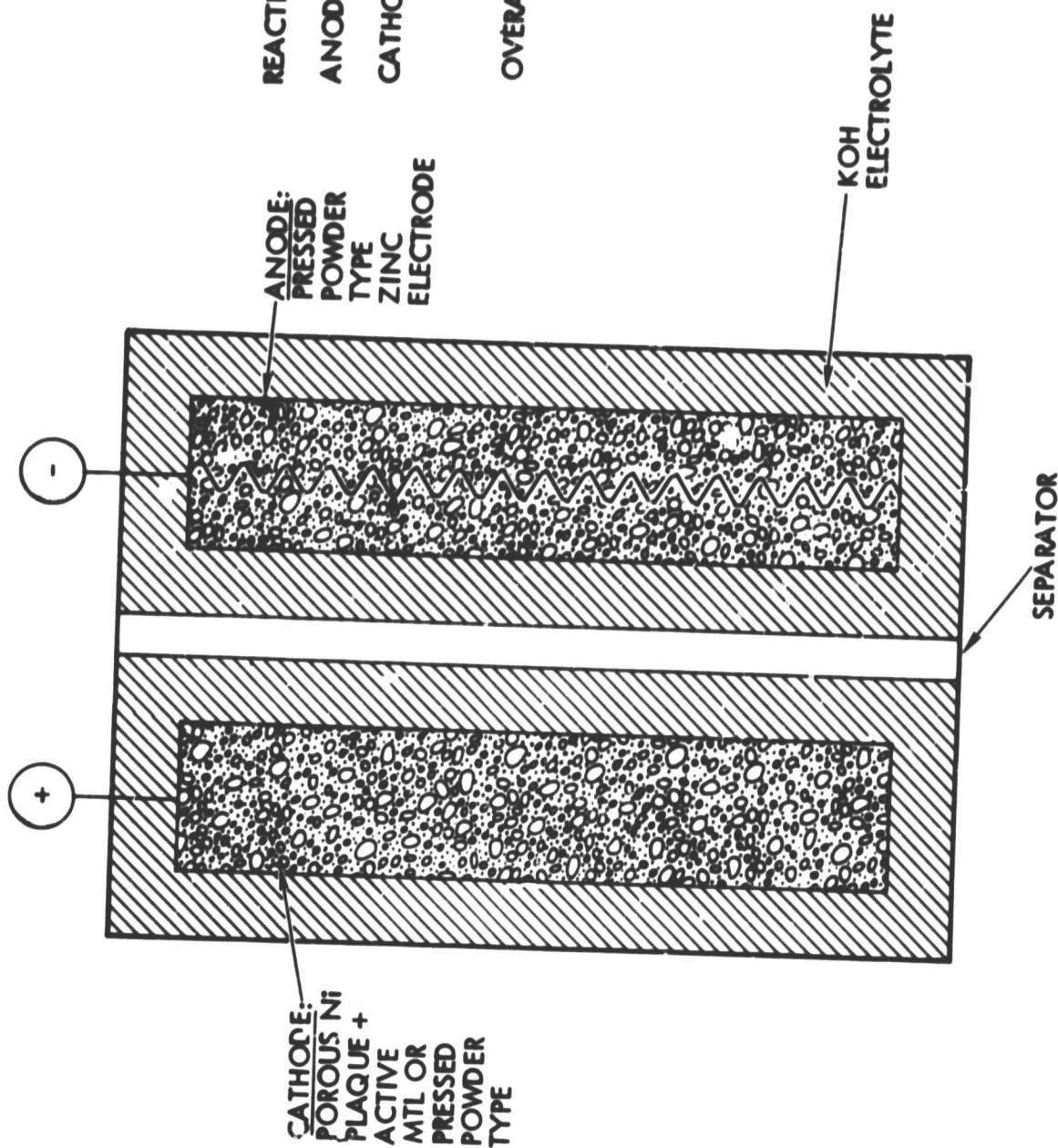
Projected cost of the nickel-hydrogen system is \$64/kWh. Round-trip energy efficiency is estimated to be between 60% and 70%. Cycle life is expected to be 10,000 cycles at 80% DOD. Pending continuance of adequate funding, the system should be available by 1990.

K. NICKEL-ZINC SYSTEM -- GOULD*

A schematic diagram of the nickel-zinc system is given in Figure 6-15, which also shows the electrochemical reactions that take place within the system during charge and discharge. The system operates at ambient or slightly above ambient temperature. The system is classified as an alkaline-type battery because it employs potassium hydroxide as electrolyte. The zinc anode is comprised of pressed

*Reference 37.

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REACTIONS



Figure 6-15. Nickel-Zinc System (Gould)

zinc-oxide powder on a screen current collector. The nickel cathode is either the sintered or pressed type as described for the nickel-hydrogen cell.

Nominal discharge voltage for this system is 1.6 volts per cell. End of discharge voltage is 1.5 volts per cell. Nominal charge voltage is 1.8 volts per cell. End of charge voltage is 1.9 volts per cell.

A major area of concern with this system is cycle life of the zinc electrode. Another is the use of costly nickel. Further, the cells are not sealed and evolve small amounts of hydrogen while on charge; without adequate ventilation this could pose a safety threat.

A sizeable program is underway at Gould to develop the nickel-zinc system for electric vehicle propulsion. Funding is at a level of about \$2M per year. Development programs are also underway on this system at Energy Research Company and Yardney. The largest cell size developed by Gould to date is 950 AH. Gould has demonstrated 300 cycles on a 400 AH vehicle size cell. They are developing a pilot plant that can produce 1000 electric vehicle batteries (25 kWh each) per year. Gould is scheduled to deliver 15 electric vehicle batteries (25 kWh each) to Argonne by June 1980.

Projected cost of the nickel-zinc battery is \$108/kWh. Round-trip energy efficiency is estimated to be 90%. Cycle life is expected to be 2000 cycles at 40% DOD. Pending continuance of adequate funding, the system should be available by 1985.

L. HYDROGEN-CHLORINE SYSTEM -- BROOKHAVEN NATIONAL LABORATORY*

A schematic diagram of Brookhaven National Laboratory's (BNL) hydrogen-chlorine system is given in Figure 6-16, which also shows the electrochemical reactions that take place within the system during charge and discharge. The system operates at a slightly elevated temperature of 80° to 100°C. During charge, hydrogen and chlorine are formed from hydrochloric acid at the anode and cathode, respectively and transferred to external storage tanks. During discharge, the gases are returned to their respective electrodes and react to form hydrochloric acid. The cell stack is quite compact and employs a cation transfer membrane to separate the hydrogen and chlorine compartments. This membrane is DuPont's Nafion, the same employed in the General Electric zinc-bromine cell. Hydrogen ions are transported across the membrane to maintain charge neutrality.

The system operates at relatively constant voltage during both charge and discharge. Nominal discharge voltage is 0.9 volts per cell. Nominal charge voltage is 1.4 volts per cell.

*Reference 38.

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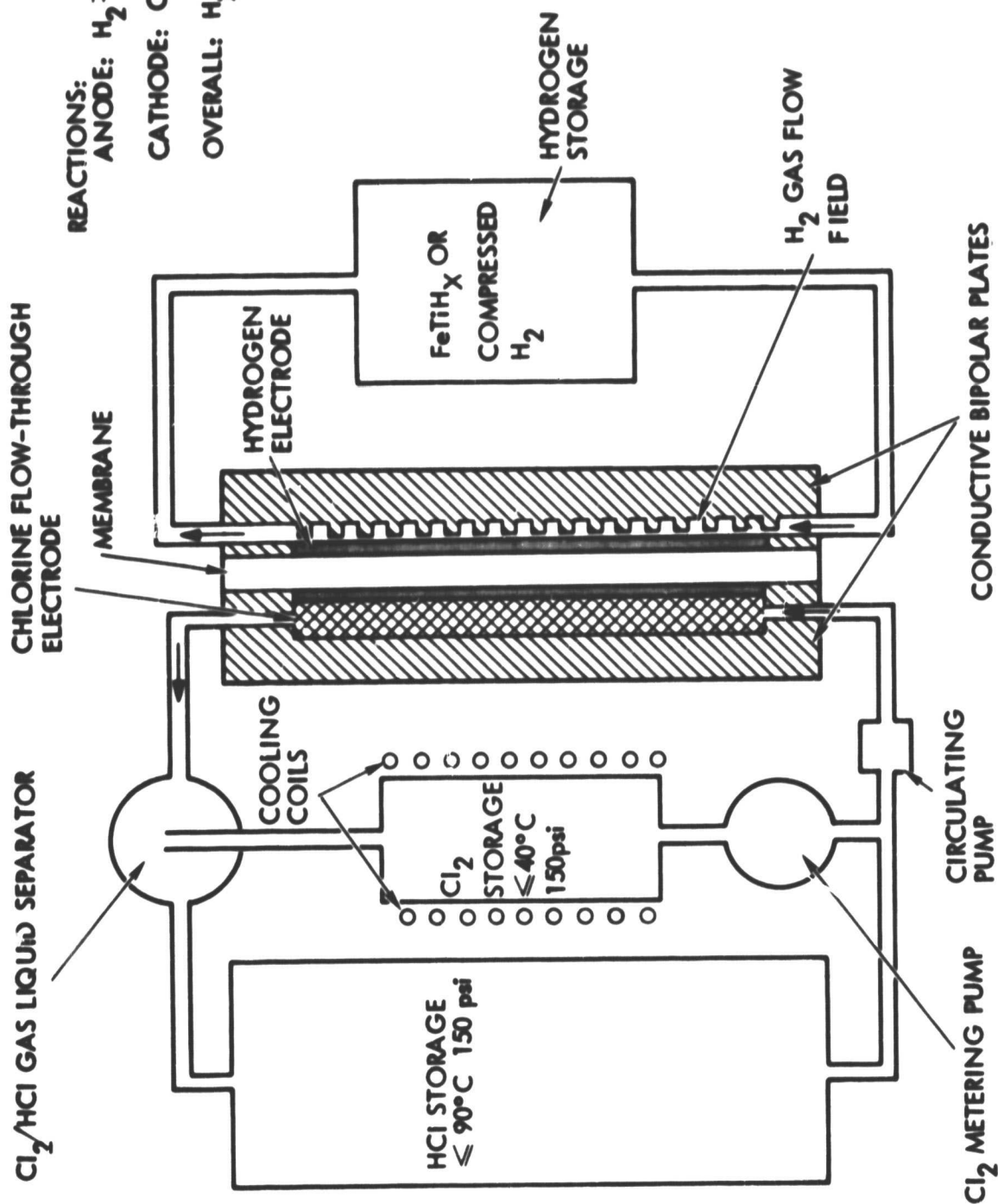
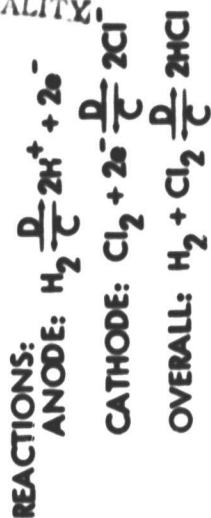


Figure 6-16. Hydrogen-Chlorine System (Brookhaven National Laboratory)

One area of concern is the high pressure storage of hydrogen (similar to the nickel-hydrogen system). Another area of concern is whether materials can withstand the corrosiveness of chlorine over the long term.

A small program is underway at Brookhaven National Laboratory to develop this system for utility load-leveling applications and storage for photovoltaic plants. The funding level is about \$100K per year. Brookhaven has subcontracted programs with De Nora, an Italian company, to study plant design and costs, and with General Electric to assemble and conduct parametric studies on a 15 We breadboard model of the system.

Projected cost of the hydrogen-chlorine system is \$81/kWeh. Round-trip energy efficiency is estimated to be 65%. Sufficient data has not been obtained to project cycle life. The system is in such an early state of development that it is not possible to project when it will be available.

M. OTHER SYSTEMS

Appendix D presents results of a brief communication with Chloride Silent Power in England on their Na-S system. Chloride's projected costs are higher than those projected by Dow, Ford, and General Electric on their Na-S systems. Also, Chloride projects lower cycle life than all of the above.

Bell Laboratories, Exxon, and EIC Co. are in the early stages of developing a new class of rechargeable cells*. These are based on lithium anodes, dichalcogenide cathodes, and an organic solvent with a lithium salt electrolyte. These operate at ambient temperature and deliver high specific energy density. Sufficient data has not been obtained to assess the merits of these new cells in solar thermal applications.

*References 39, 40, 41, 42.

SECTION VII

BALANCE OF SYSTEM STORAGE PLANT DESIGN CONSIDERATIONS AND COST*

A. INTRODUCTION

The balance of system storage plant will be required if electrochemical storage and conversion is required. This balance of system design will be dependent on whether a DC or AC link system is used. The AC-link system is shown in the single line diagram of Figure 7-1. The basic elements of the system consist of the following:

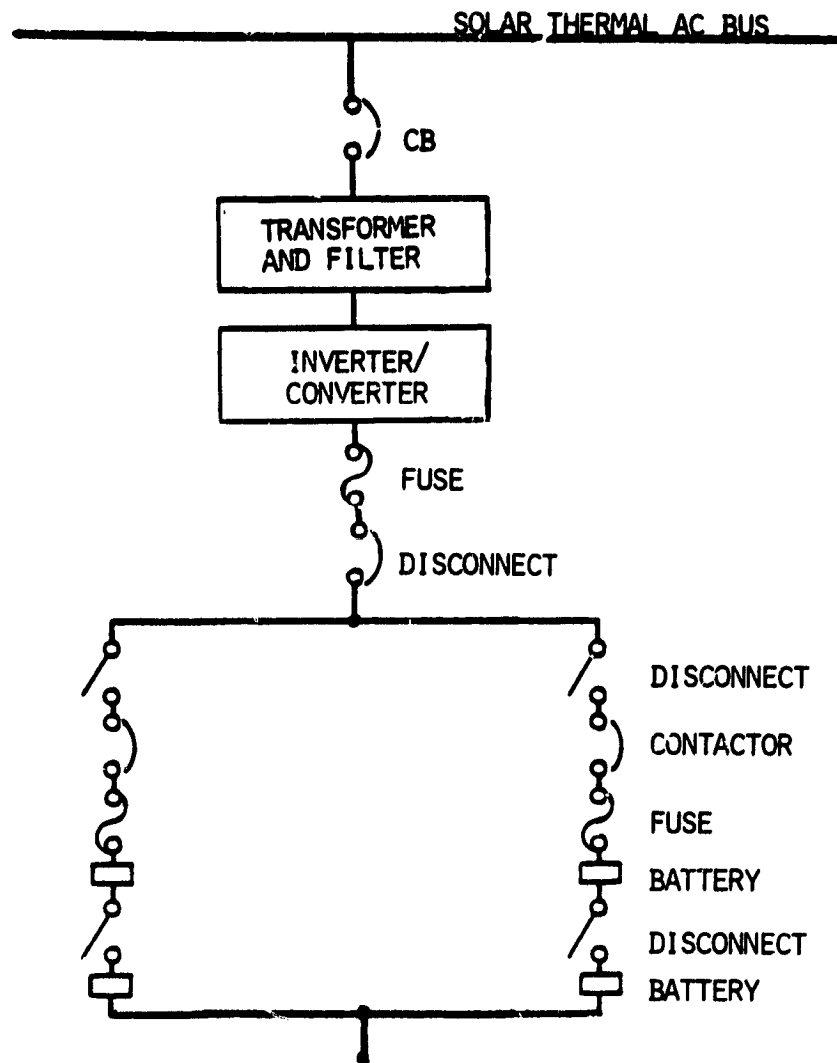
- (1) Battery
- (2) Battery disconnects, fuses, and contactors
- (3) Inverter/converter
- (4) Inverter/converter DC disconnects and fuses
- (5) Inverter/converter output transformer and bus circuit breakers

For the AC-link solar thermal plant the battery storage plant may be considered separately from the solar thermal plant without battery storage. The storage plant can be located within the proximity of the utility interface equipment associated with the solar thermal plant. Interface can be at the solar thermal plant, high-voltage AC bus or at the point of utility interface. The interface design is dependent on cable, transformer and switchgear costs. If the storage plant is remote from the solar thermal plant, interface will be at the utility grid. Remote location of the battery plant may be desirable due to possible ecological and maintenance requirements. If the battery plant is close to the utility distribution centers, battery plant efficiency will be greater due to reduced power cable losses.

Battery and inverter/converter efficiency are very important factors. The effects of improved efficiency are detailed in Section IV. The main advantages of improved efficiencies are reduced cycle life costs and reduced bus bar energy costs.

The storage plant requirements have been addressed in some detail for existing lead-acid and advanced lead-acid systems. There is only limited available cost and plant information dealing with mature, advanced battery systems other than lead acid. A broad series of issues require additional detailing. These issues relate to high

*References 6, 9, 14, 15, 17, 19, Appendix E.



- NOTES:**
1. Number of strings will depend on manufacturer's battery rating.
 2. System grounding options: negative ground or battery center-tap ground.

Figure 7-1. A Single Line Diagram for a 10 MWe - 5 Hour Storage Plant with AC-Link Interface

voltage battery plants, grounding methods, lightning protection, reliability, safety and maintainability problems, battery charging techniques and profiles.

Firm price estimates for storage/converter plants are not possible, particularly for non-lead-acid plants. Estimates will be possible when plant system design has been optimized, manufacturing expertise acquired and cost reduction approaches implemented. Advanced battery plant cost will be addressed later in this section.

B. LEAD-ACID STORAGE PLANT COST CONSIDERATIONS

The electrochemical energy storage plant cost will encompass many diversified subsystem and labor components. For a lead-acid plant these generally consist of the following, in addition to the battery. (See Tables 7-1 and 7-2).

- Battery shipping, installation, DC bus and disconnects.
- Inverter/converter and equipment installation.
- Civil/structural: battery building, control building, shop building.
- Mechanical, piping, cooling: cell handling equipment, make up water system, cooling system.
- Electrical: station power, building service and lighting.
- Instrumentation: battery system, control room, other.
- Yardwork.
- Distributables: 60% of direct field labor.
- Engineering services: percentage of fixed cost, labor.

A detailed cost breakdown is provided in Table 7-1 for a lead-acid battery storage plant. The data provided is for a mature plant with five hours of storage utilizing sealed cells in a tiered configuration. Table 7-1 provides a cost breakdown exclusive of battery module costs. These costs relate to an AC-link system. It should be noted that for a DC-link system the inverter/converter is an integral component of the solar thermal plant, as a result the analysis in Table 7-1 is valid only for an AC-link solar thermal plant.

C. ADVANCED BATTERY STORAGE PLANT COST CONSIDERATIONS

Advanced battery storage plant costs will be kept to a minimum by means of component modularization and reduction in building requirements for the battery or the inverter/converters. Advanced batteries will be assembled in modules consisting of a multiplicity of

Table 7-1. Balance of System Costs ¹ and Existing Lead-Acid Storage System.

Item	\$/kWe	\$/kWeh
Batt. Inst. Shipping, DC Bus		5.20
Inverter/Converter	60.502	
Civil/Structural	1.00	4.20
Mechanical, Piping, Cooling		3.80
Electrical	1.00	1.10
Instrumentation	2.50	1.90
Yardwork	1.00	0.60
Distributables	4.00	2.20
Engineering Services	4.10	3.30
Subtotal	74.10	22.30
Contingency:		
11% of \$/kWe	8.15	
26% of \$/kWeh		5.80
1976 Total Cost	82.25	28.10
1979 Total Cost (1.23 x 1976 cost)	101.20	34.50

¹1976 Dollars

²See Table 8-1 for inverter/converter cost, see Appendix B for assumptions.

cells. These modules will be factory preassembled. The electrochemical cost itemized in Table 7-3 reflects module cost and not cell costs. There will be a minimum of installation required at the prepared construction site because of the preassembled modules. In a similar fashion the inverter/converter modules will be factory preassembled. At the construction site the modules will be set in place and bus bars bolted together.

The plant costs for batteries other than advanced lead acid have not been analyzed in a comprehensive manner*. Due to the lack of firm

*Ni-Zn, Ni-H₂, Ni-Fe, Fe-Air BOS costs will be similar to those of the advanced lead-acid (Table 7-2).

data relating to individual battery systems, approximations of costs have been used for this study in order to help provide some measure of battery system ranking. Installation and other costs vary as indicated in one study according to battery type from \$5/kWeh to \$12/kWeh*. Another study indicates costs for NaS and ZnCl₂ at 10-15% of battery kWeh costs plus 15% of inverter/converter costs. These costs are detailed in Tables 7-2 and 7-3.

Table 3 presents a summary of balance of system costs for the advanced systems. The costs are given in terms of \$/kWe + \$/kWeh. The costs for the advanced Pb-Acid system are relatively firm, since they are based on realistic projections of current costs. The Fe-Air, Ni-Fe, Ni-H₂, and Ni-Zn systems are similar in configuration and would be installed in a manner similar to the advanced Pb-Acid system. Therefore, the costs for these systems are assumed identical to those for the advanced Pb-Acid system. The other advanced systems are much different in configuration and would be installed in a different manner than the above systems. No firm guidelines were available for estimating the costs for these systems, and assumptions were required to arrive at the indicated costs. (See Appendix B). It should be noted that there is currently a number of detailed studies in process to more accurately define BOS systems costs. Detailed information was not available at the time this study was done. The basic methodology used in this study to identify BOS costs, other than the power conditioner and associated power components, is limited. As a result, there may be wide error bands in BOS costs particularly for the systems defined above as "Other Advanced Systems".

For the purposes of this study (Table 7-3) total battery and inverter/converter costs are determined for a 10 MWe system with a five hour discharge capability. Installation and other costs will be 18% of this total. Thus, plant costs will consist of battery, inverter/converter, installation and other related costs.

D. CURRENT EFFORTS IN BATTERY STORAGE PLANTS (LOAD LEVELING)

The balance of system storage plant for the AC-link solar thermal plant is essentially configured similar to a conventional battery, inverter/converter load-leveling plant. Substantial effort is in process on this type of multi-megawatt, load-leveling plant. Two main areas of effort are of interest. The first is the BEST facility in New Jersey, for which the Public Service Electric and Gas Co. (PSE&G) has responsibility for construction, design and testing. The sources of funds are from DOE and EPRI. The test facility will be the site for evaluation of advanced battery systems and advanced inverter/converter systems which may make electrochemical storage of electricity commercially feasible by 1985. The data collected will help battery developers and utility companies to make decisions relating to load-leveling systems application and cost.

*1975 dollars, for a 10 MWe plant with 5-hr storage.

Table 7-2. Cost of 10 MWe, 5-Hour Electrochemical Storage Plant for Solar Thermal Applications (mid-1979 dollars)

System	BOS Costs	
	\$/kWe	+ \$/kWh
Advanced Pb-Acid	101.20	34.50
Na-S (GE)	95.12	8.15
Na-S (Ford)	95.12	8.15
Na-S (Dow)	95.12	6.25
Fe-Cr Redox (LeRC)	101.73	4.15
Zn-Cl ₂ (EDA)	105.20	5.10
LiM-FeS (Argonne)	95.12	10.20
Zn-Br ₂ (Gould)	91.90	9.25-11.15
Zn-Br ₂ (Exxon)	91.90	6.05
Zn-Br ₂ (GE)	91.90	10.95
Fe-Air (Westinghouse)	101.20	34.50
Ni-Fe (Westinghouse)	101.20	34.50
Ni-Fe (EP)	101.20	34.50
Ni-H ₂ (ERC)	101.20	34.50
Ni-Zn (Gould)	101.20	34.50
H ₂ -Cl ₂ (BNL)	95.12	15.30

Table 7-3. Balance of System Costs for Advanced Storage Systems

Electrochemical System	Electrochemical Cost in \$10 ³	Balance of System Cost in \$10 ³	Total Cost in \$10 ³
Advanced Pb-Acid	5800-6500	2737	8537-9237
Na-S (GE)	2150	1358	3508
Na-S (Ford)	2150	1358	3508
Na-S (Dow)	1650	1263	2913
Fe-Cr Redox (LeRC)	2420	1225	3655
Zn-Cl ₂ (EDA)	1940	1304	3244
LiM-FeS (Argonne)	2700	1462	4162
Zn-Br ₂ (Gould)	2450-2950	1382-1476	
3832-4426			
Zn-Br ₂ (Exxon)	1600	1221	2821
Zn-Br ₂ (GE)	2900	1466	4366
Fe-Air (Westg)	1600	2737	4337
Ni-Fe (Westg)	2700	2737	5437
Ni-Fe (EP)	3250	2737	5987
Ni-H ₂ (ERC)	3250	2737	5987
Ni-Zn (Gould)	5400	2737	8137
H ₂ -Cl ₂ (BNL)	4050	1717	5767

This facility is configured to allow for the testing of a multiplicity of existing and advanced battery systems. The initial operational system will use existing lead-acid batteries with a line commutated inverter/converter for battery charging and inversion from DC to AC. Future testing will be with advanced batteries. This facility will provide invaluable information relating to performance of advanced batteries, battery operation and maintenance, safety, plant costs, inverter/converter performance, utility interface and control methodologies.

In addition to the BEST facility, another major facility is now being configured. This program is titled "SBEED". DOE Chicago Operations Office, with possible EPRI participation, has requested and received quotes for this system. The size of this facility will be configured at 10 MWe. Battery plant discharge will be for a period of three-five hours with a seven hour recharge period. The system will be approximately an order of magnitude larger than the BEST facility and will be a demonstration plant rather than a test facility. The objectives of this load-leveling system are as follows:

- Design, construct, test, accept and operate a Storage Battery Electric Energy Demonstration (SBEED) plant.
- Integrate advanced batteries to system for evaluation purposes.
- Operate commercially for up to nine and one half years.
- Conduct the SBEED program in a fully operational commercial-size plant, using normal utility operating and maintenance personnel to respond to actual utility load demands. Address power system issues related to the battery on the power system, including controllability, dynamic response, stability consideration, harmonics and resonance.
- Identify a better method of meeting utility peak load demand, increasing system operation flexibility, switching to alternate fuels for peak-load requirements, and favorably impacting the cost of electricity.

- Operate commercially for up to nine and one half years.
- Conduct the SBEED program in a fully operational commercial-size plant, using normal utility operating and maintenance personnel to respond to actual utility load demands. Address power system issues related to the battery on the power system, including controllability, dynamic response, stability consideration, harmonics and resonance.
- Identify a better method of meeting utility peak load demand, increasing system operation flexibility, switching to alternate fuels for peak-load requirements, and favorably impacting the cost of electricity.

SECTION VIII

INVERTER/CONVERTER COST AND DESIGN CONSIDERATIONS*

A. INTRODUCTION

The function and cost of the inverter/converter are significant considerations in a battery storage plant. The purpose of the inverter is to provide a means of power conversion from a DC bus to a three-phase AC bus by means of solid state static devices. The purpose of the converter is to provide a means of battery charging in a controlled manner as required by battery charge power management considerations. The battery charging also is accomplished by solid state static devices. For battery charging, the converter processes AC three-phase power and provides controlled DC power to the battery.

Current production of inverter/converter equipment generally will have separate inverter modules and separate converter modules. Systems that will be used in the BEST facility and the SBEED facility and other advanced systems will use a power module that has capability of operating either as an inverter or a converter.

Inverters currently being produced are primarily used in four distinct market areas (see Appendix E).

- (1) Adjustable speed, alternating-current motor drives: adjustable speed, AC motor drives are used extensively in railroad AC drives, machine tool AC motor control, and in textile fiber AC motor drives.
- (2) Frequency changers: frequency changers have been used to convert 60 Hz to 50 Hz, 400 Hz and other frequencies.
- (3) Uninterruptible power supplies: uninterruptible power supplies are used in conjunction with batteries to back up critical buses when utility power fails. They are generally used with lead-calcium batteries designed for float service. Other batteries such as NiCad and Pb-Sb are also used in this application.
- (4) VAR generators: VAR generators are used in power factor correction, voltage control and to reduce the effects of arc furnaces on the utility line.

Inverters have been in operation on a large scale since 1961. Inverter power capacities have ranged in size from kilowatt to multi-megawatt systems. Inverters have accrued multi-millions of hours of operation with a high degree of reliability. Large scale installations have had mean time between failures (MTBF) of from 10,000 to 150,000 hours. The technologies and production techniques of existing inverter systems are quite mature.

*References 1, 2, 7, 9, 19, Appendix E.

Inverter systems above 50 kWe generally are silicon controlled rectifiers (SCR). The inverter technologies utilized in present inverter systems up to 10 MWe are primarily of the forced-commutated types, although line commutated inverter types have significant application in utility interactive systems.*

B. COST CONSIDERATIONS

Present costs (1979) of inverter/converter systems for uninterruptible power supplies above 1 MWe are relatively uniform in \$/kWe. For systems under 1 MWe inverter/converter costs increase as size is reduced. Most companies in this business are in volume production and price their equipment as follows:

Type	Selling Price \$/kWe 1979
Separate Inverter and Converter	216
Inverter/Converter*	173

*The projected costs for this system (single unit inverter/converter) does not include the development cost for a controlled converter for battery charging.

Costs for improved inverter/converters systems for uninterruptible power supplies have been provided by Exide Power Systems (see Appendix E) as follows: (separate inverter and converter)

KVA	Selling Price* \$/kWe
10	500
1000	200

*1985 time frame (1979 dollars).

*When an SCR is turned on, it continues to stay on until power is interrupted and drive signals are removed, or drive signal is removed and a reverse voltage is applied across the SCR. Thus, in a forced-commutated inverter, reverse voltage is applied artificially in order to turn off the SCR switch. In line-commutated types the utility bus AC voltage is used to reverse bias the SCR in order to turn off the device. (See Glossary).

The costs for advanced inverter/converters for the balance of system described in this study, with a rating of 10 MWe is provided in Table 8-1. It should be noted that inverter/converter costs are contingent upon a number of important factors:

- (1) DC bus voltage
- (2) Megawatt capacity
- (3) Overload requirements
- (4) SCR voltage safety factor requirements
- (5) Turnoff time rating for SCR's forced commutation inverters
- (6) Environmental factors (ambient temperature, etc.)
- (7) SCR current capacity
- (8) Battery voltage operating range
- (9) Cooling methods

Inverter/converter costs vary as a function of DC bus voltage. Table 8-1 shows a substantial cost reduction for higher voltage systems. The costs for a 750 VDC (max) system are \$113/kWe to \$81/kWe for a 2200 VDC (min) system.

The pricing in terms of \$/kWe varies incrementally in terms of megawatts and voltage so that there may be substantial price increases for a relatively small increase in the system power rating or DC voltage rating. This is due to the manufacture of optimal building blocks predicated upon available semiconductor and switchgear costs. In a similar fashion, reduction in power rating may not decrease total costs with respect to the 10 MWe rating. The costs for a particular system must be considered with respect to available standard systems. (See Table 8-1).

Costs will be increased as the voltage safety factors (for SCR) is increased and overload capacity is increased.

A reduction in cost of 2-4% of the converter costs for the redox and zinc-bromine battery is due to a reduced battery voltage range.

The cost of \$75/kWe (Table 8-1) for future generation systems reflects a number of cost reductions, such as improved device (SCR) turnoff time and reduced commutation component requirements.

C. DESIGN CONSIDERATIONS

Current production high power inverter systems generally operate with DC bus voltages from 200 VDC to 600 VDC. These inverters may be used in the battery storage plant for the solar thermal system. Due to the need for a new generation of inverter/converters with high efficiency and low cost, more advanced inverter/converter types will be utilized in the mature solar thermal storage plant.

Table 8-1. Inverter/Converter Costs*
10 MWe System (1979 Dollars)

DC Bus Voltage	\$/kWe Present Generation and Advanced Technology	\$/kWe Future Generation
750 VDC maximum	113	
1500 VDC maximum	106	
1700 VDC minimum		84 (at 1700 VDC min.)
2200 VDC minimum	81	75 (\$60/kWe for 14 MWe system)

*The costs are FOB manufacturing plant and include both battery interfaces and utility interfaces at 13.8 kV. Costs are from various studies and manufacturers and reflect production of 1000 MWe of inverters per year.

Two types of advanced inverters are available. There are the forced-commutated and the line-commutated types. Improved costs and greater module power occurs at voltages up to 3000 volts DC. Efficiency of the advanced inverters will be higher than that of present inverters. Efficiency figures for the inverter/converters described will be as follows:

Load	Efficiency Discharge Mode*	Efficiency Charge Mode*
25%	94%	93%
100%	96%	96%
(2200 VDC Minimum Bus)		
*Reference 18.		

Both inverter technologies (forced commutated and line commutated) have a number of advantages and disadvantages. These trade-offs are reasonably well detailed in the literature. Since there is only limited field experience with the advanced inverter/converter technologies, both line and force commutated inverters will be utilized. It will take approximately three years of field testing and cost evaluation to determine the most desirable technical and cost effective approach.

Certain characteristics of the forced commutated inverter offer interesting opportunities for application to a solar thermal plant. The alternator (induction type), connected to a heat engine requires line capacitors. These are required to provide excitation current to the alternator. The capacitor value is approximately 10 KVAR for 30 kWe each alternator. The capacitors may be reduced in size by proper logic control of the inverter, enabling the inverter to supplement this excitation current requirement. This is similar to having a rotary synchronous capacitor on the line to control alternator excitation. This possible cost saving should be taken into account in the economic considerations of the solar thermal system.

Typical dimensions and weights of a 10 MWe inverter/converter installation are as follows: The system will be modular in design and will be delivered on pallets which can be trucked to the plant site. The inverter will be delivered in 2 parts consisting of pallets 2 & 3. Pallets 1, 2, and 3 will be delivered to the construction site and installed. Eighteen bus bars will be bolted together; a multipin connector will be provided for control. The modules will be factory assembled, thereby reducing on-site construction costs.

10 MWe Inverter/Converter Mechanical Assemblies*

Pallet #	Function	Size	Weight #
1	Transformer	7'x13'x15'	63,000
2	Inverter	17'x36'x15'	53,000
3	Inverter	8-1/2'x36'x15'	73,000

*Reference 18.

SECTION IX

CONCLUSIONS

Conclusions of this study are presented in two parts. The first part deals with the battery or electrochemical portion of the storage plant. The second part deals with the balance of system required for the storage plant.

A. ELECTROCHEMICAL

In regard to the electrochemical category, the following conclusions have been reached:

- (1) The cost and performance of existing lead-acid batteries have been established for near-term demonstration programs. Depending on the given application, these batteries will cost from \$170 to \$220/kWeh, deliver 2000 cycles at 80% DOD, and operate at an efficiency of 70% to 85%.
- (2) Eleven types of advanced electrochemical systems have been identified and described in this report. These are the advanced lead-acid, sodium-sulfur, iron-chromium redox, zinc-chlorine, lithium metal-iron sulfide, zinc-bromine, iron-air, nickel-iron, nickel-hydrogen, nickel-zinc, and hydrogen-chlorine systems.
- (3) The projected cost and performance of these advanced systems have been established for the 1985 to 1990 time frame. Costs of these systems will range from about \$33 to \$130/kWeh. Cycle lives will range from 1000 to 10,000 cycles at 80% depth of discharge. Efficiencies will range from 50% to 90%.
- (4) The cost, performance and availability parameters are the best estimates that could be supplied by vendors and the engineering assessments of the authors. Determination of uncertainty bands for these parameters would require additional efforts.

B. BALANCE OF SYSTEM

In regard to the balance of system category, the following conclusions have been reached:

- (1) Balance of system costs for lead-acid battery plants have been broken down into ten elements. These elements are: a) installation, shipping and DC bus, b) converter, c) civil and structural, d) mechanical piping and cooling, e) electrical, f) instrumentation, g) yardwork, h)

distributables, i) engineering services, and j) contingency. Normalized costs have been assigned to each of these elements in terms of \$/kWe and/or \$/kWh.

- (2) The inverter/converter constitutes a substantial portion of balance of system costs. Two types of inverters have been considered. These are line-commutated and forced-commutated inverters. Costs of both types are diminished with increased bus voltage, especially in the range of 600 to 3000 volts.
- (3) Inverter/converter costs are sensitive to operation with DC bus voltage: higher DC bus voltages reflect lower costs. With advanced inverter/converter systems, it would be desirable to operate at bus voltages up to 3000 volts in order to reduce BOS costs.
- (4) The converter sizes for the zinc-bromine and redox systems may be smaller since these systems may be charged at constant voltage, thereby reducing the voltage range of the inverter/converter. Hence, these systems may cost less.
- (5) Total storage plant costs were established for 10 MWe - 5 hour plants based on the advanced electrochemical systems. Total costs ranged from about \$2.8 M to \$9.2 M for the various systems.

SECTION X

RECOMMENDATIONS

In order to assess and direct technology developments in the field of electrochemical storage systems and be prepared to incorporate these systems (when required) in solar thermal plants, follow-on tasks are recommended in three areas: battery, balance of system, and total system. Specific subtasks in each of these areas are outlined below in order of priority.

A. BATTERY

- (1) Conduct in-depth analysis of advanced batteries, including:
 - (a) Battery cost
 - (b) Heating, ventilation, and air conditioning requirements
 - (c) Safety and reliability issues
 - (d) Effect of system bus voltage on battery design
 - (e) Probability of availability of advanced batteries
 - (f) Uncertainty band of cost and availability of advanced batteries
 - (g) Battery efficiency improvement analysis
 - (h) Reliability of cycle life projections
 - (i) Manufacturability
 - (j) Availability and projected cost of raw materials
- (2) Identify other new potential electrochemical technologies
- (3) Analyze battery integration into solar thermal plant, including:
 - (a) System operational procedures
 - (b) Fault and protection considerations
 - (c) Battery plant design
 - (d) Parasitic power requirements
 - (e) Safety and reliability considerations

- (f) Source and load characteristics
- (g) Operational modes (constant current, constant voltage, and constant power profiles)
- (h) Interfaces and control functions associated with battery control system
- (4) Conduct failure mode analysis for battery strings, including:
 - (a) Battery failure mechanisms
 - (b) Failed battery bypass implementation
- (5) Develop complete battery specification, including:
 - (a) Voltage rating
 - (b) Power rating
 - (c) Overload rating
 - (d) kWh rating
 - (e) Recharge time
 - (f) Efficiency
 - (g) Cycle life
 - (h) Module electrical and mechanical requirements
 - (i) Heating, ventilation, and air conditioning requirements
 - (j) Ambient and environmental specifications
- (6) Conduct performance and cost analysis for existing and advanced batteries for duty cycles other than 10 MWe - 5 hour. This will include:
 - (a) Development of cost matrices (\$/kWe and \$/kWh) as a function of KVA for larger and smaller systems
 - (b) Development of the same cost matrices for other discharge times
 - (c) Determination of efficiency and cycle life for other discharge times
- (7) Analyze salvage value of existing and advanced systems

B. BALANCE OF SYSTEM

- (1) Conduct detailed inverter/converter analysis, including:
 - (a) Identification of useable and preferential electronic technologies
 - (b) Determination of methods and technologies for module protection
 - (c) Cost reduction
 - (d) Efficiency improvement
 - (e) Identification of new technological cost breakthrough areas
 - (f) Identification of available componentry
 - (g) Determination of effect of advanced battery types on design and cost
 - (h) Performance specification
- (2) Analyze use of higher system voltage, including:
 - (a) Cost reduction
 - (b) Efficiency improvement
 - (c) Associated design problems
 - (d) Componentry identification
- (3) Continue the balance of system analysis for the advanced battery systems, including:
 - (a) Requirements study for advanced battery plants
 - (b) Cost analysis for advanced battery systems
 - (c) Examination of alternative configurations and associated costs
 - (d) Analysis of safety and reliability
- (4) Conduct performance and cost analysis for balance of system for duty cycles other than 10 MWe - 5 hour. This will include:
 - (a) Development of cost matrices (\$/kWe and \$/kWeh) as a function of KVA for larger and smaller systems
 - (b) Development of the same cost matrices for other discharge times

- (c) Determination of efficiency and cycle life for other discharge times

C. TOTAL SYSTEM

- (1) Perform studies of operation, maintenance, control and safety issues of advanced battery storage plants
- (2) Perform analysis and design of storage plants for near- and far-term demonstration programs in support of the solar thermal project
- (3) Perform cost studies of advanced battery storage plants
- (4) Develop storage plant specification including:
 - (a) Electrical performance requirements
 - (b) Environmental requirements
 - (c) Heating, ventilation, and air conditioning requirements
 - (d) Construction and installation
 - (e) Fault protection
 - (f) Safety and maintainability

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APPENDIX A

BATTERY CONFIGURATION QUESTIONNAIRE*

1. Cost small quantity (single system) 50 MWe-hr, 10 MWe-5 hrs, \$/kWe, \$/kWe-hr, \$/kWe-hr delivered
2. Cost large quantity 1000 MWe-hr/yr, 10 MWe-5 hrs, \$/kWe, \$/kWe-hr, \$/kWe-hr delivered
3. Information on installation costs
 - A. Will battery be enclosed?
 - B. Cooling requirements
 - C. Maintenance requirements
 - D. Cost of installation
4. Operating costs
 - A. Material costs
 - B. Heating/cooling costs
 - C. Maintenance costs
5. Parasitic Power Costs
 - A. Heating/cooling
 - B. Mechanical & electrical pumps & other equipment
 - C. Control components
6. Efficiency
 - A. $\text{kWe-hr efficiency (charge) full load} = (\text{kWe-hr out/kWe-hr in}) \times 100$
 - B. Efficiency at 1/2 load
 - C. What is parasitic power requirement?
 - (1) What are parasitic components?

*Telephone Survey

7. Battery characteristics (module)

- A. Module voltage rating**
 - (1) Float
 - (2) Nominal
 - (3) End of discharge voltage
- B. Turn on and turn off voltage and current requirements (how to get battery on line and off line)**
- C. Battery weight**
- D. Battery dimension**
- E. kW-hr rating**
- F. Battery current capacity**
- G. Total battery bank voltage, any limitations 400 - 3000 volts DC**
- H. Recharge requirements (profile)**
- I. Problem areas**
 - (1) Parallel operation
 - (2) Module failure
 - (3) Contamination
 - (4) Safety
- J. Special conditioning requirements**

8. Operating temperature

- A. Ambient nominal**
- B. Internal battery temperature**
- C. Temperature operating range**
- D. Special cooling/heating requirements**

9. Life

- A. Cycle life**
 - (1) Cycle life--depth discharge - temperature - cost
- B. Shelf life**

- C. Cycle life as a function of ambient temperature
 - D. Salvage possibilities
- 10. Battery construction
 - A. Anode
 - B. Cathode
 - C. Electrolyte
 - D. Case & mechanical features
- 11. Availability
 - A. When will developmental battery systems be available?
 - B. When will production batteries be available?
- 12. System compatibility
 - A. System interface requirements
 - (1) Protection - bypass
 - (2) Converter interface
 - B. Special installation requirements
- 13. Logistics
 - A. Battery delivery methods & packaging

APPENDIX B

DATA BASE AND CALCULATIONS IN TABLES 1 - 4

Inflation Rate:

Studies regarding costs of various electrochemical storage systems were made in the base year 1978. However, the data throughout this report were updated to mid-1979. An inflation factor of 8% increase* was used to update figures from 1978 to mid-1979 dollars. In Table 2, all 1976 dollar figures were multiplied by a factor of 1.23 to bring them up to date with other tables in 1979 dollars.

It should be noted that the inflation factor is not very precise in updating the dollar value. For example, in this study, the CE plant cost index was used and it includes: equipment, machinery, supports, construction labor, buildings, engineering and supervision, etc., but it does not take into account unusual price increases in some materials. Hence, in using the figures in Tables 1 - 7 it should be understood that average inflation numbers are used.

Inverter/Converter Efficiency:

Throughout the report, it is assumed that the AC-link type of storage system is used. Therefore, the efficiency of the storage system is a factor of 1) battery efficiency, 2) inverter/converter efficiency, 3) transformer/filter efficiency, and 4) plant cable losses. Cable losses are considered to be small with respect to the total throughput efficiency of the storage system. Then the storage system efficiency can be approximated by the following:

$$\eta_{\text{storage}} = \eta_{\text{inverter}} \times \eta_{\text{converter}} \times \eta_{\text{battery}}$$

where

$$\eta_{\text{battery}} = \text{efficiency of storage system}$$

$$\eta_{\text{converter}} = \text{efficiency of converter}$$

$$\eta_{\text{inverter}} = \text{efficiency of inverter}$$

An efficiency of 96% for inverter and converter was selected (see Section VIII-C). These values correspond to a 100% load operation and a 2200 VDC minimum bus voltage.

The value \$60.50 \$/kWe for inverter/converter cost in Table 2 was taken from Table 8-1. The value shown in Table 8-1 is \$75

*CE plant cost index was chosen as the most appropriate economic index for this study. (Chemical Engineering, July 1979 issue).

in 1979 dollars for a 2200 VDC, 10 MWe system. \$75 = \$60.50 in 1976 dollars to be used in Table 2.

Due to the similarity of the Fe-Cr redox and Zn-Cl₂ battery plant and due to the substantial differential in battery initial \$/kWe cost, the \$/kWe component for the BOS calculation of the Redox battery is assumed to be the same as that of the Zn-Cl₂ battery. As additional BOS cost information becomes available these numbers will be modified.

In addition, since the converter/inverter cost for the Zn-Br₂ and the Fe-Cr Redox systems is cheaper than for the other systems (see conclusion (4) on page 9-2) a value of \$72 was used instead of the \$75 for the converter/inverter cost for these two systems.

BOS Costs:

The following is assumed to compute BOS costs for the advanced storage systems in Table 3:

- (1) The costs for advanced Pb-Acid, Fe-Air (Westinghouse), Ni-Fe (Westinghouse), Ni-Fe (Eagle Picher), Ni-H₂ (ERC), and Ni-Zn (Gould) are assumed to be similar to those of existing lead-acid batteries as in Table 2.
- (2) The BOS costs of the other batteries are computed according to the following formula (see References 4, 5):

$$\text{BOS cost} = .15 \times (\text{Battery initial cost} + \text{converter/inverter cost}) + \text{converter/inverter cost} + \text{contingencies}$$

where

$$\text{Contingencies} = .11 \text{ of cost/kWe and } .26 \text{ of cost/kWh}$$

APPENDIX C

ECONOMIC ANALYSIS*

C-1. Introduction

This appendix outlines the economic analysis performed to compare solar thermal plants using different electrochemical storage systems.

The solar plants considered are rated at 10 MWe and are expected to have a service life of 30 years.

Two methods of comparison are used:

- (1) Comparison of the solar plants by their levelized energy cost, over the 30 years service life (Comparison 1).
- (2) Comparison of the storage systems by the cost of energy output from storage (Comparison 2).

These methods are explained in the following paragraphs, together with a summary of the calculational procedures. The interpretation of the results is then presented.

C-2. Methodology of Comparison 1

Comparison 1 is made by calculating the levelized cost of delivered energy per kWh. This is a number representing the average of the distribution of all costs over the service life of the plant. This cost includes:

- (1) The capital costs and the operation and maintenance (O&M) costs of the field for solar energy collection.
- (2) The capital costs and the O&M costs of the power plant for energy conversion.
- (3) The capital costs and O&M cost of the storage system.

The costs of the field and power plant are based on a reference solar thermal plant. This is done in order to maintain a common base for the comparison of the storage systems within a solar plant. The reference plant specifications are as follows (Reference C-4):

Type	Paraboloidal Dish Stirling
Power Rating	10 MWe
Capacity Factor	0.3
Collector Field Area	1,000 m ²
Reference System	75% efficient, having a
Battery (Redox-LeRC)	service life of 30 years

*References C-1, C-2, C-3

The results of this comparison are presented in Table C-1 and Figure C-1. Table C-2 gives the actual dollar values of capital investment for the plant. In this comparison, the system with the lowest levelized energy cost is the most desirable.

SUMMARY OF CALCULATIONAL PROCEDURE FOR COMPARISON 1

Assumptions

1. Power plant is rated at 10 MWe
2. Daily hours of operation on stored energy = 5 hours/day
3. Daily hours of insolation = 10.8 hours
4. Cycles of charge/discharge per month = 27
5. Service life 30 years or 9720 cycles of charge/discharge
6. Capacity factor = $\frac{10.8 \text{ hrs} + 5 \text{ hrs}}{24 \text{ hrs}} = 0.6583$ (distributed dish)
7. Electrical converter/inverter efficiency = 0.922
8. Reference battery efficiency = .75
9. Present worth of O&M costs for field and power plant based on the reference plant specifications = $\$2.619 \times 10^6$ (base year 1972)
10. Present worth of field and power plant cost, based on reference plant specifications = $\$11.243 \times 10^6$ (base year 1979)*
11. Operation and maintenance costs for the battery energy storage system = 0.5 mills per kWh of delivered energy (for the year 1979)
12. Annual interest rate = 8.6%
13. Rate of general inflation, $g = 6\%$ (constant)
14. Rate of capital escalation, $g_c = 6\%$ (constant)
15. Rate of O&M costs escalation, $g_x = 7\%$ (constant)
16. Capital investments for field and power plant are directly proportional to the overall efficiency of the solar thermal plant.

*See Reference C-4, Figure B-13.

17. The cost of the last replacement battery is proportional to the fraction of battery life used. That is, if for example, the last replacement battery is used for half its life then its cost will be half of the full replacement cost.

Calculations

1. Total present worth of all investments:

$$I_t = I_{\text{field}} + I_{\text{power plant}} + I_{\text{storage}}$$

$$(I_{\text{field}} + I_{\text{power plant}}) = (I_{\text{field}} + I_{\text{power plant}})_{\text{Ref.}} \times \frac{\eta_1}{\eta_2}$$

$$(I_{\text{field}} + I_{\text{power plant}})_{\text{Ref.}} = \$11.24 \times 10^6$$

$$\frac{\eta_1}{\eta_2} = \frac{T + \frac{\eta_r}{\eta_s} \frac{\eta_c}{\eta_c} T'}{T + \frac{\eta_r}{\eta_s} \frac{\eta_c}{\eta_c} T'} = \text{Ratio of plant efficiency with reference redox storage to plant efficiency with other type of advanced storage battery.}$$

where

T = 10.8 hours daily insolation

T' = 5 hours on storage

η_r = efficiency of reference Redox system = 0.75

η_c = inverter/converter efficiency* = 0.922

η_s = advanced system battery efficiency

*See Assumption in Appendix B.

2. Each battery system has a life expressed as the number of cycles of charge and discharge. Call this RLIFE.

The replacement life of a battery will be:

$$\frac{\text{RLIFE cycles}}{27 \text{ cycles/month}} = \text{RMOS (months)}$$

That is, each battery will have a life of RMOS months, after which it must be replaced.

The number of replacement batteries required will be the "greatest integer function" of $\frac{360 \text{ months}}{\text{RMOS months}} = \text{REP}$

C-2

That is, dropping the decimal part of the quotient:

$$(\text{REP}) = \text{NREP}$$

3. Consider one year = 365 days = 12 months

$$\text{Average days per month} = 365/12 = 30.417$$

Allowing for inoperation of the plant on cloudy days and during days when the plant is shut down for maintenance, it is assumed that the battery storage would not operate for 10% of the time. This translates to 27 days/month during which the storage will be operating.

Assume the batteries are charged and discharged once a day for each month, then the number of charge/discharge cycles will be 27 cycles/month.

4. To find I_{storage} :

$$I_{\text{storage}} = (\text{Balance of System Cost}) + (\text{Initial Battery Cost}) + (\text{Net Present Worth of Replacement Batteries})$$

$$\begin{aligned} &= \text{FC} + \text{RI} + \sum_{J=1}^{\text{NREP}} \text{RI} \left(\frac{1 + g_c}{1 + i} \right)^{J \times \text{RMOS}} \\ &\quad - \text{RI} \left[1 - (\text{REP} - \text{NREP}) \right] \times \left(\frac{1 + g_c}{1 + i} \right)^{\text{NREP} \times \text{RMOS}} \end{aligned}$$

where,

FC = balance of system cost

RI = initial battery cost

$$\sum_{J=1}^{\text{NREP}} \text{RI} \left(\frac{1 + g_c}{1 + i} \right)^{J \times \text{RMOS}} = \text{present worth of all replacement batteries.}$$

$$\text{RI} \left[1 - \left(\frac{360}{\text{RMOS}} - \text{NREP} \right) \right] \left(\frac{1 + g_c}{1 + i} \right)^{\text{NREP} \times \text{RMOS}} = \text{present worth of unused portion of last replacement batteries}$$

g_c = annual capital escalation rate = 6% (= .004868 monthly)

i = annual interest rate = 8.6% (= .006899 monthly)

5. Present worth of all O&M costs:

$$M_t = M_{\text{field}} + M_{\text{power plant}} + M_{\text{storage}}$$

$$(M_{\text{field}} + M_{\text{power plant}}) = \$2.619 \times 10^6$$

6. The monthly storage O&M cost will be:

$$\begin{aligned} AM &= \left(\frac{27 \text{ days}}{\text{month}} \right) \left(\frac{\text{plant rating}}{\text{in kW}} \right) \left(\frac{5 \text{ hours}}{\text{day}} \right) \left(\frac{\text{cost of O\&M}}{\text{in \$/kWh}} \right) \\ &= \left(\frac{27 \text{ days}}{\text{month}} \right) (10 \text{ MW} \times 1000 \frac{\text{kW}}{\text{MW}}) \left(\frac{5 \text{ hours}}{\text{day}} \right) (0.5 \times 10^{-3} \text{ \$/kWh}) \\ &= \$675/\text{month} \end{aligned}$$

$$M_{\text{storage}} =$$

$$AM \left[1 - \left(\frac{1 + g_x}{1 + i} \right)^{360} \right] \left(\frac{1 + g_x}{i - g_x} \right) \left[\left(\frac{1 + g_x}{1 + g} \right)^{12} \right] \quad (2000-1979)$$

where

i = monthly interest rate = .006899 (8.6% on annual basis)

g_y = monthly escalation rate of O&M costs = .005654 (7% on annual basis)

g = monthly general inflation = .004868 (6% on annual basis)

$$M_t = M_{\text{field}} + M_{\text{power plant}} + M_{\text{storage}}$$

$$= \$2.619 \times 10^6 + (675) \left[1 - \left(\frac{1 + g_x}{1 + i} \right)^{360} \right] \left(\frac{1 + g_x}{i - g_x} \right) \left(\frac{1 + g_x}{1 + g} \right)^{252}$$

7. Levelized Energy Cost

$$ECYB = \frac{F_i I_t + F_m M_t}{CF \times P \times 8760 \text{ hrs}} \quad (\text{in mills/kWh})$$

ECYB = The levelized energy cost per unit of energy delivered, in base year dollars (mills/kWh)

F_i = .1568, factor which annualizes investment

F_m = .0939, factor which annualizes O&M present value

I_t = Present value of total capital investment

M_t = Present value of O&M costs

CF = Capacity factor, .6583

P = Power rating, 10 MWe

8. Cost of energy delivered to storage per month:

$$\begin{aligned} \text{CEB} &= \frac{\text{Plant rating}}{\eta_s \eta_c} \left(\frac{\text{hours of storage}}{\text{per cycle}} \right) \left(\frac{\text{number of cycles}}{\text{per month}} \right) \left(\frac{\text{cost}}{\text{per kWh}} \right) \\ &= \frac{(10 \text{ MWe} \times 1000 \text{ kWh})}{\eta_s (.922) \text{ MWe}} \left(\frac{5 \text{ hours}}{\text{cycle}} \right) \left(\frac{27 \text{ cycles}}{\text{month}} \right) \left(\frac{\text{CPK}}{1000} \right) \\ &= \frac{1.464 \times 103}{\eta_s} \text{ CPK } (\$/\text{month}) \end{aligned}$$

Where CPK is the cost per kWh (mills/kWh)

9. Cost of energy output from storage, per month:

$$\begin{aligned} \text{CES} &= \left(\frac{\text{cost of energy}}{\text{to storage}} \right) + \left(\frac{\text{monthly}}{\text{O\&M costs}} \right) + \left(\frac{\text{amortized}}{\text{investment}} \right) \\ &= \text{CEB} + \text{AM} + I_{\text{storage}} \left[\frac{1}{\left(1 - \left(\frac{1 + g_x}{1 + i} \right)^{360} \right) \left(\frac{1 + g_x}{1 - g_x} \right)} \right] \end{aligned}$$

The cost of energy output from storage (mills/kWh) is given by,

$$\frac{\text{CES (1000 mills/\$)}}{(10000 \text{ kW}) \frac{5 \text{ hrs}}{\text{cycle}} \frac{27 \text{ cycles}}{\text{month}}}$$

Table C-1. Advanced Electrochemical Energy Storage Costs
for a 10 MWe Solar Thermal Plant

Storage System Costs							
	1	2	3	4	5	6	7
Battery Type	Battery Initial Cost \$/kWh	Balance of Sys. Costs \$/kWh	Total Stor. System Initial Cost \$/kWh	Storage Replacement Cost \$/kWh	Number of Replacements	Battery Efficiency (%)	Levelized Cost of Delivered Energy mills/kWh
Fe-Cr Redox (LeRC))	48.4	24.5	72.9	(-1.3)***	0	69	45.0
Zn-Br ₂ (Exxon)	32.0	24.4	56.4	20.7	1	74	45.2
Na-S (Ford)	43.0	27.2	70.2	27.9	1	69	48.6
Na-S (Dow)	33.0	25.3	58.3	51.5	3	90	48.7
Zn-Cl ₂ (EDA)	38.8	26.1	64.9	47.7	2	74	50.6
Ni-H ₂ (ERC)	65.0	54.7	119.7	(-1.8)***	0	70	51.8
Na-S (GE)	43.0	27.2	70.2	87.0	3	76	56.5
LiM-FeS	54.0	29.2	83.2	84.2	3	85	57.0
Zn-Br ₂ (Gould)	59.0	30.2	89.2	119.0	3	70	64.1
Zn-Br ₂ (GE)	58.0	30.0	88.0	157.0	4	75	63.6
Ni-Fe (Westg)	54.0	54.7	108.7	147.0	4	60	71.5
Ni-Fe (EP)	65.0	54.7	119.7	176.0	4	70	76.0
Fe-Air Adv.	32.0	54.7	86.7	197.0	9	50	76.5
Pb-Acid	130.0	54.7	184.7	127.0	2	85	76.7
Ni-Zn (Gould)	108.0	54.7	162.7	293.0	4	90	95.7

- Notes:
- 1) All costs are for base year 1979, in 1979 dollars.
 - 2) All values are based on a 10 MWe power plant and 5 hours of operation from storage.
 - 3) To convert the cost values to costs for the first year of commercial operation (year 2000) multiply by 3.4.

*Initial capital costs & levelized cost of delivered energy.

**Includes salvage value based on prorating residual battery life beyond 30 years plant life.

***In these cases, 97% of the originally installed battery life was used and the negative quantities correspond to a small salvage value.

Table C-2. Capital Investments for 10 MWe Solar Thermal Plant
with an Advanced Electrochemical Storage

Battery Type	1 Battery Initial Cost \$x10 ⁶	2 Storage Balance of System Cost \$x10 ⁶	3 Storage System Initial Cost \$x10 ⁶	4 Storage Replace- ment Cost \$x10 ⁶	5 Field and Power Plant Costs \$x10 ⁶	6 All O&M Costs \$x10 ⁶
Fe-Cr Redox (LeRC)	2.420	1.225	3.645	(-0.065)**	11.24	2.858
Zn-Br ₂ (Exxon)	1.600	1.220	2.820	1.035	11.06	2.858
Na-S (Ford)	2.50	1.358	3.508	1.395	11.24	2.858
Na-S (Dow)	1.650	1.263	2.913	2.575	10.72	2.858
Zn-Cl ₂ (EDA)	1.940	1.304	3.244	2.385	11.28	2.858
Ni-H ₂ (ERC)	3.250	2.737	5.987	(-0.091)**	11.43	2.858
Na-S (GE)	2.150	1.358	3.508	4.350	11.21	2.858
LiM-FeS	2.700	1.462	4.162	4.210	10.89	2.858
Zn-Br ₂ (Gould)	2.950	1.501	4.459	5.950	11.43	2.858
Zn-Br ₂ (GE)	2.900	1.499	4.399	7.850	11.24	2.858
Ni-Fe (Westg)	2.700	2.737	5.437	7.350	11.82	2.858
Ni-Fe (EP)	3.250	2.737	5.987	8.800	11.42	2.858
Fe-Air Adv.	1.600	2.737	4.337	9.850	12.23	2.858
Pb-Acid	6.500	2.737	9.237	6.356	10.89	2.858
Ni-Zn (Gould)	5.400	2.737	8.137	14.650	10.72	2.858

- Notes:
- 1) All costs are base year 1979, in 1979 dollars.
 - 2) All values are based on a 10 MW plant and 5 hours of storage operation.
 - 3) To convert the cost values to costs for the first year of commercial operation (year 2000) multiply by 3.4.
 - 4) The costs in columns 4, 5 and 6 are present worth values.

*Includes salvage value based on prorating residual battery life beyond 30 years plant life.

**In these cases, 97% of the originally installed battery life was used and the negative quantities correspond to a small salvage value.

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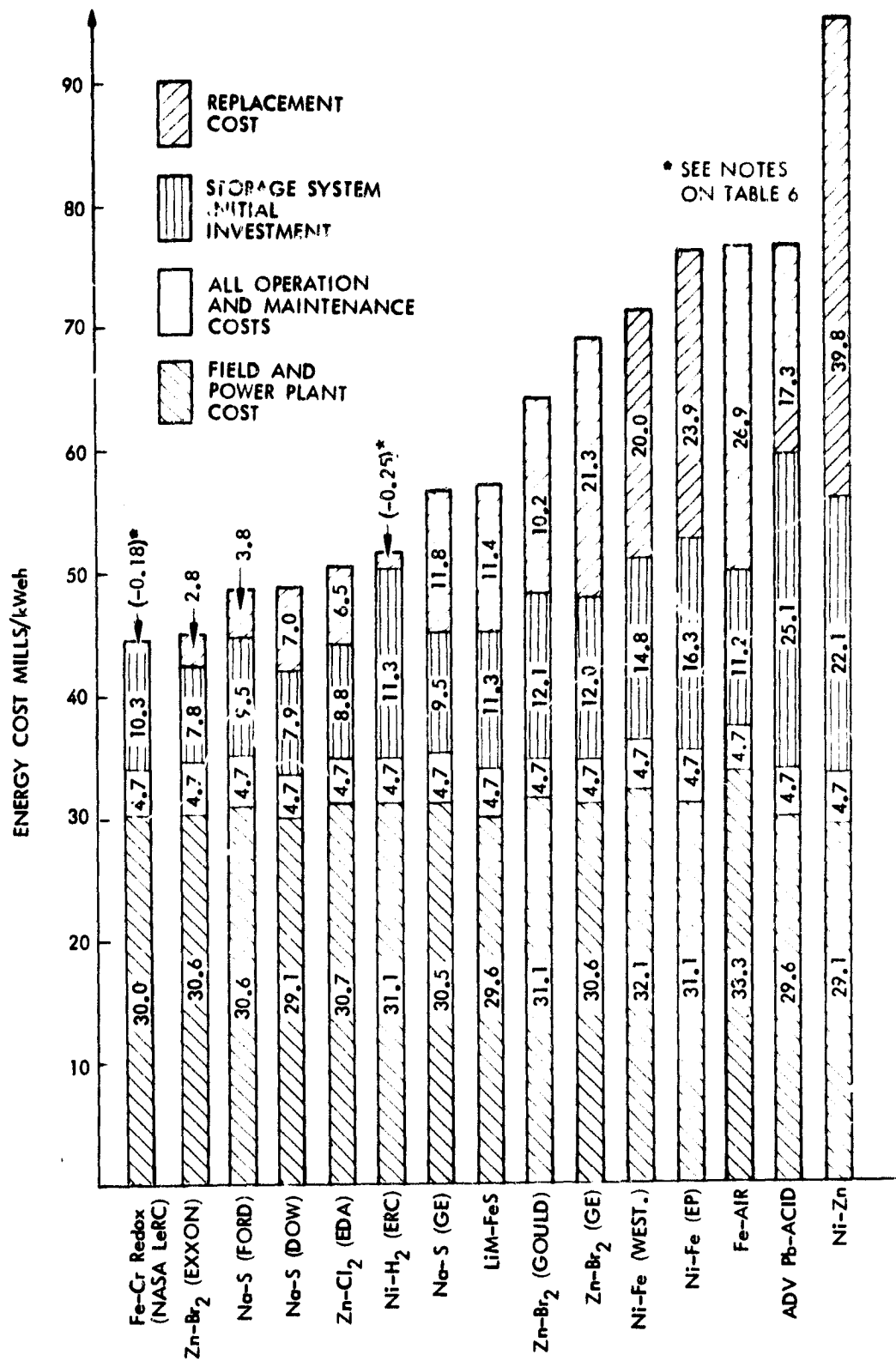


Figure C-1. Levelized Energy Cost Showing Contributing Cost Factors

C-3. Methodology for Comparison 2

Comparison 2 is made by calculating the storage output energy cost per kWh. This is the cost at which the storage plant would have to deliver stored energy in order to recover the full cost of the storage plant over the service life. Note that this comparison is only dependent on the cost of energy input to the storage device and the storage efficiency, and it evaluates the battery systems when used as external storage devices connected to a constant power grid.

The results are presented in graphical form by plotting the cost of energy output from the storage versus the cost of energy input to the storage. The slope of the curve gives an indication of the storage efficiency: the more efficient energy storage devices have smaller slopes.

The y-intercept of the curve is indicative of the initial and repeated cost of the energy storage system: the higher the y-intercept, the higher is the overall cost of the battery.

The results of this comparison are presented in Figure C-2.

The assumptions used here are the same as in Comparison 1.

The cost of energy delivered by storage in 1979 dollars:

(cost of energy) =

$$\left(\begin{array}{c} \text{cost of energy} \\ \text{input to} \\ \text{storage} \end{array} \right) + \left(\begin{array}{c} \text{O\&M} \\ \text{cost of} \\ \text{storage} \end{array} \right) + \left(\begin{array}{c} \text{cost of} \\ \text{initial} \\ \text{capital} \\ \text{investment} \end{array} \right) + \left(\begin{array}{c} \text{cost of} \\ \text{replacement} \end{array} \right)$$

C-4. Interpretation of Results

The results obtained here for both comparisons are based on a 10 MWe solar thermal plant for 5 hours of energy storage operation. All cost values are for the base year 1979 expressed in 1979 dollars.

Comparison 1 finds the levelized cost of delivered energy per kWh. This cost is dependent on the initial capital investment for the storage, the field and power plant costs, and the number of replacements required to fulfill the 30-year service life. The contribution of each cost factor is shown graphically in Figure C-1. The field and power plant costs are dependent on the storage efficiency. The higher the efficiency, the lower the energy cost contribution. As shown in Figure C-1, the energy cost contributions from the field and power plant for the various systems are very close. It is also observed that these costs are the major contributors to the total energy cost.

The effect of the operation and maintenance costs is minimal and it is the same for all the systems at 4.7 mills/kWh.

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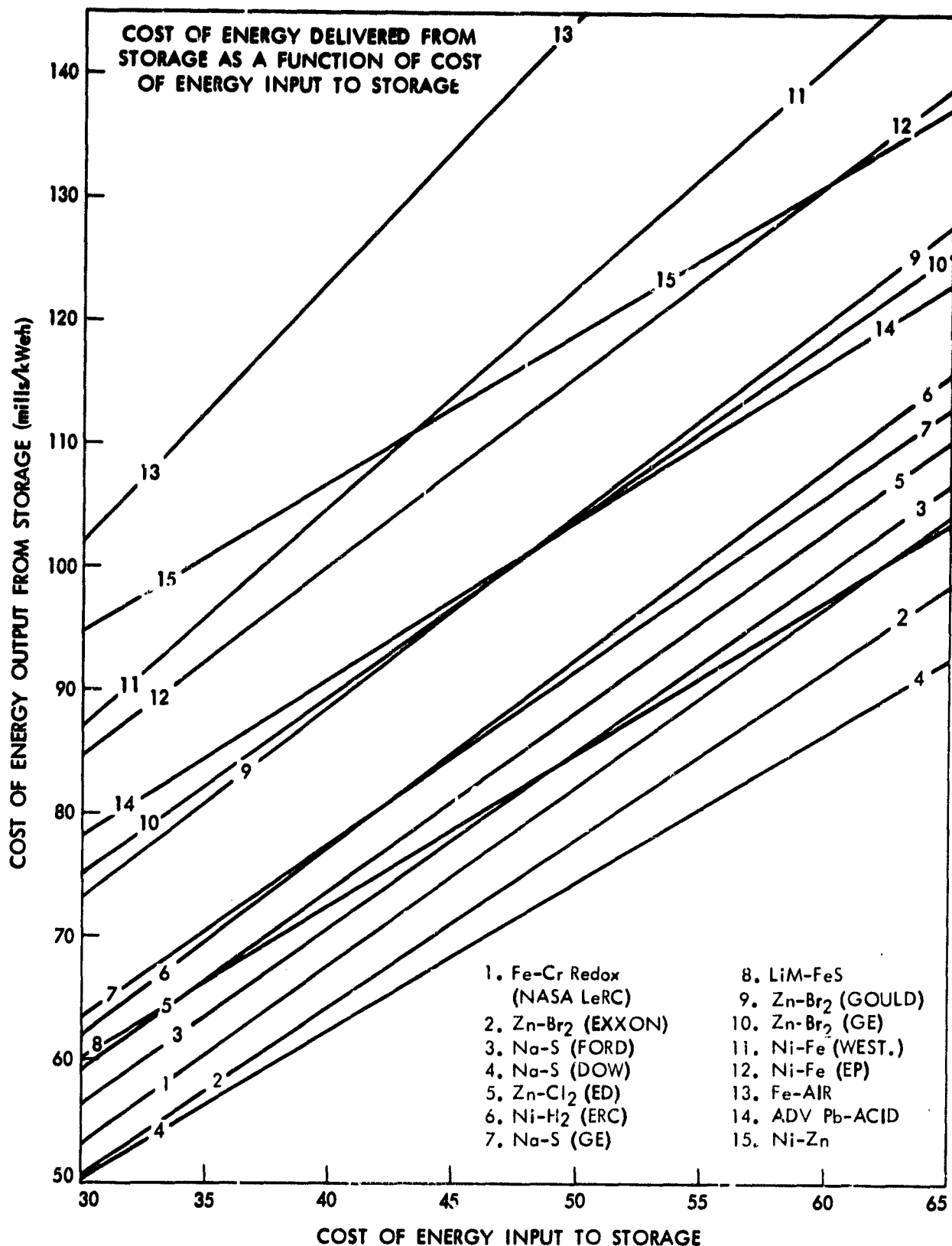


Figure C-2. Results of Comparison 2

The effect of the number of replacements of storage is also shown in Figure C-1. Storage systems with many replacements contribute more to the overall levelized energy cost. For example, from Table C-1, column 1, it is observed that the Zn-Br₂ (Exxon) system and Fe-Air system both have a battery cost of \$32.0/kWh (equivalent to 1.6 million 1979 dollars of capital investment). However, it is observed that Fe-Air requires over 9 replacements, whereas Zn-Br₂ (Exxon) requires only 1.9 replacements. This difference is evident in the total replacement costs of these batteries (Table C-1, column 4). The effect of the battery cost can be determined by comparing any two storage systems requiring the same number of replacements but having different initial costs. For example, Zn-Br₂ (GE) and Ni-Zn (Gould) both require 4.9 replacements, but the higher initial cost of the Ni-Zn causes the large energy cost contribution from the replacement costs as shown in Figure C-1.

It will be observed that since the replacement costs contribute a large portion of the total energy cost, differences in the storage efficiency, O&M costs, and balance of plant costs do not appear to be important.

The levelized energy cost gives an overall average which considers the effects of all the contributing cost factors. The most desirable storage system is that which gives the lowest levelized energy cost. From Table C-1 or Figure C-1 the Zn-Br₂ (Exxon) and Fe-Cr (Redox) both meet this requirement. The advantage of the Redox battery over the other, however, is the fact that its service life is greater than 30 years and, therefore, requires no replacements.

The storage systems are also compared according to Comparison 2. The results of this comparison are shown in Figure C-2. This figure indicates the energy delivery cost from storage in order to recover all the costs incurred over the service life. This value is plotted versus the cost at which energy is delivered to the battery for storage.

In this comparison, it is assumed that there is a fixed energy input into all the systems (10 MWe). The cost of this energy then becomes dependent on the system efficiency. Note that in this case the costs of the field and power plant are not considered for the comparison. In Comparison 2 the Na-S (Dow) battery shows a lower storage system cost than the Zn-Br₂ (Exxon) or the Fe-Cr (Redox) batteries. The reason for this is the 90% efficiency of this system versus the lower efficiencies of the latter two systems. In comparing the Na-S (Dow) and the Zn-Br₂ (Exxon), Table C-2 shows that both systems have comparable initial investment costs. Even though the Na-S (Dow) has a higher replacement cost, the cost of its operation for a fixed amount of input energy will be lower because of the high efficiency.

In conclusion, if the criterion for choosing a battery system is to be the levelized energy cost, then the first four batteries in Table 6 should be given equal consideration since their levelized costs are very close. In such a case, the next determining factor will be the number of replacements. Therefore, if we consider a battery storage

system integrated with a solar thermal plant, the Fe-Cr (Redox) system will be the most desirable choice.

Considering the storage systems independently of a solar thermal plant, Comparison 2 indicated that the most attractive choice will be the Na-S (Dow) battery system.

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- C-1. Manvi R., and Fujita, T., "Economics of Internal and External Energy Storage in Solar Power Plant Operation," Proceedings of the 12th IECEC, Washington, D.C., August 28 - September 2, 1977.
- C-2. Doane, J.W., et al, "The Cost of Energy From Utility-Owned Solar Electric Systems." A Required Revenue Methodology for ERDA/EPRI Evaluation, ERDA/JPL-76/3, June 1976.
- C-3. El Gaoalawi, N., Hill, G., Bowyer, J., and Slonski, M., "A Modularized Computer Simulation Program for Solar Thermal Power Plants," JPL Internal Document 5102-80, July 1978.
- C-4. Latta, A.F., Bowyer, J.M., Fujita, T., and Richter, P.H., "The Effects of Regional Insolation Differences Upon Advanced Solar Thermal Electric Power Plant Performance and Energy Costs," JPL Publication 79-39, March 15, 1979.

APPENDIX D

COMMUNICATION WITH CHLORIDE SILENT POWER LTD.

February 20, 1979

Attn.: Harvey A. Frank
Electrochemical Power Group
Jet Propulsion Laboratory
Pasadena, California

Sodium Sulfur Batteries

1. Energy efficiency is 85 percent (current efficiency is 100 percent, voltage efficiency is 85 percent).
2. Projected cost is about \$100/kWeh but is expected to reduce with increasing production.
3. Projected cycle life is 1500 deep cycles.
4. Will be available commercially CY 1985 earlier for evaluation.
5. Largest unit to date is 70 kWeh, 30 kWe.
6. CSPL has staff of 50.

Please write or phone me for further information.

Regards,

Geoff Lomax
Applications Manager
Chloride Silent Power Limited
England

APPENDIX E

POWER CONDITIONING FOR LARGE SYSTEMS INTEGRATED WITHIN A UTILITY GRID WORKSHOP SUMMARY*

Stanley Krauthamer
Workshop Chairman
Jet Propulsion Laboratory
Pasadena, California

Introduction

This document represents a summary of the workshop on "Power Conditioning for Large Systems Integrated Within a Utility Grid" prepared by the Workshop Chairman.

With the advent of the rapid development of alternate energy and storage sources the methodology of interfacing this energy into a utility grid provides an interesting challenge. The interfacing power block between the alternate sources and the utility grid is labeled a power conditioner. The alternate energy source and the requirements for interface with the utility grid places certain design and performance constraints upon the power conditioner.

The basic issues dealing with power conditioners were broken down and discussed with respect to the following categories:

- State of Technology
- Available Technologies
- Hardware Availability
- Power Conditioner Costs
- Performance and Operational Requirements
- Requirements to Stimulate Development
- Technology Development Recommendations and Comments

The working group was made up of approximately 24 persons (the exact number varied as several persons rotated between working groups). Included in the above was a panel of six persons, all specialists from private industrial concerns. Thirteen of the group members represented private industrial concerns, three members were from utility organizations, one represented a university and three represented government agencies and national organizations.

The working group was addressed by the Chairman and the six panel members. The discussions were informal in nature and addressed the various relevant systems and power conditioner issues.

*Workshop for Alternative Energy Technologies, U.S. DOE, Denver, CO, May 9, 1979.

State of Technology

Power conditioner technology is a reasonably mature technology. Substantial experience has been gained over the past number of years. Four major areas of power conditioner technology are as follows:

1. Uninterruptible Power Supplies (UPS)
2. AC Adjustable Speed Inverter Drives
3. High Voltage DC Transmission (HVDC)
4. VAR Generators

UPS systems have been produced on a rather extensive scale in the sizes of 15-600 kW. Systems have been built as large as 2.5 MWe with one unit rated at 8 MWe, in process of the Social Security Administration. These systems are generally 30 types operating at a DC bus voltage of 120 VDC - 600 VDC. Voltage regulation is +1% and harmonic distortion is 5%. Typical mechanical dimensions for a 600 kW UPS is 7' x 16' x 3'. The inverters are forced commutated types using either six or 12 pulse inverters. The basic problems of parallel operation have been mastered indicating that the typical UPS system has the potential of being connected to the utility bus with provisions for proper logic control.

There are 1000 UPS installations in the U.S. Ten systems are rated at 2.5 MWe. The UPS systems are manufactured on a volume basis and the market for these systems is quite competitive. UPS pricing can be used to arrive at base line costs for large power conditioners for alternate energy sources. UPS units have proved to be highly reliable. On a production run of 90 UPS units for the FAA an MTBF of 17,000 hours was established (Garrett AiResearch).

AC adjustable speed inverter drives have been used for AC motor speed control for the past 20 years. Thousands of these systems, 10 kW - 25 MWe, have been in operation. These systems have been used by textile fiber manufacturers, machine tool manufacturers and the railroad industry. The systems generally operate over a speed range of 6:1 and voltage regulation of approximately +2%. The AC motors operate from low frequencies up through 400 Hz. The systems are generally forced commutated types with either 6 or 12 pulse operation. DC bus voltages range from 100 VDC - 1500 VDC.

High voltage DC transmission (HVDC) systems are used to transmit power over great distances. Generally these systems operate at voltages above 100 kV and powers in excess of 100 MWe. Systems have been in operation in Europe and the U.S. with excellent reliability records. A typical system at Eel River (280 kV) shows a 99% availability and a 96% availability for two units including planned outages. A system with 6000 SCR's (50 mm) had a failure rate of three devices in two years. Redundancy of SCR's in these systems is approximately 15%. The typical systems installed in the U.S. consist of 2-6 pulse line commutated bridges, one bridge in a wye-wye configuration and one bridge in a wye-delta configuration. This connection offers reduced harmonic distortion. For systems at 100 MWe or below series tuned filters are used to filter the 11th and 13th and higher harmonics.

VAR generators have been developed for use in cleaning up the effects of arc furnaces on the utility line. The VAR generators are line commutated phase controlled inverter switches. They are used as harmonic filters, power factor correction and a means to balance a 30 line. Total VAR generation capacity is 1200 MVAR. VAR machines are competitive with synchronous condensers and capacitor power factor correction. The VAR generator is basically a controlled inductor in parallel with capacitors usually termed a "Dynamic Steinmetz Balancer".

In recent years substantial efforts have been expended to develop advanced systems for large power conditioners. The three most notable systems are:

1. **BEST Facility:** A joint effort of DOE, EPRI and PSE&G. This facility is designed to test out advanced electrochemical storage systems for load leveling. This facility is currently being built and should be on line in the 1980 time frame.

Facility operating DC bus will be rated at 500 VDC - 1000 VDC with peak rating at 1000 VDC and 5000 amperes. The system will be under microcomputer control. Inversion technology relevant to this facility has been demonstrated by 1000 hours of operation of an inverter feeding into a utility grid (built by UTC).

2. **Consolidated Electric of New York:** This system is a joint EPRI, DOE and Consolidated Electric effort. The system is a load leveling system with a fuel cell and inverter supplied by United Technologies Corp. The system rating is 4.8 MWe with a DC bus voltage rated from 2700 VDC to 3600 VDC.

3. **SBEED:** This system is a joint EPRI and DOE program. The program objective is to field and test over a period of nine years a load leveling system rated at 10-20 MWe with electrochemical storage of from 3-5 hours. This system is currently out for competitive bid.

Available Technologies

Two technologies are currently used for large power conditioners connected to a utility grid. These technologies are the forced commutated types and the line commutated types. The forced commutated types use external methods to turn off the power SCR devices whereas the line commutated inverters use the utility grid to turn off the power SCR's. There are many advantages and disadvantages for each technology. The characteristics of these systems are available from the various power conditioner manufacturers. Once a number of systems of both technologies are integrated into a utility grid, then a proper assessment of each system can be made. The market place will be the final determinant as to which technology is technically and cost-wise the most adequate.

Hardware Availability

Various types of hardware are available either as an off-the-shelf or as a developmental type unit that will interface with a utility grid. Power ratings range from 40 kW to 14 MWe. The optimum systems from a cost point of view are available at 14 MWe from UTC and 12 MWe from Garrett AiResearch. Other vendors will likely have similar ratings. DC bus voltages will range from 2200 VDC to 3800 VDC for optimum costs. It is anticipated that most systems will have microprocessor control for operation purposes and power management purposes.

Power Conditioning Cost

Power conditioning costs vary as to technology types, MWe size and available DC bus voltages. Several of these issues are addressed in EPRI Reports RP841-1, 842, 255. Cost projections for advanced 30 UPS systems are as follows (DC input-AC output):

KVA	Selling* Price \$/kW	*1985 time frame (1979 dollars, Exide Power Systems) For DC input-AC output systems a cost of \$150/kW for 8 MWe size reflects current prices.
10	500	
1 MVA	200	
10 MVA	100	
15 MVA	85	

For the advanced technology inverters 14 MWe, 2200 VDC - 3600 VDC inverter costs are \$45/kW at a production rate of 150 units/year (1975 dollars). The cost of the advanced technology inverters can cost from five to 10 times the \$45 when quantities are quite small. It should be noted that inverters below the 14 MWe rating will show increased costs as MWe ratings are reduced (UTC).

HVDC systems are reviewed in EPRI Report RP390 with anticipated costs being \$30/kW. Current market costs reflect about \$100/kW (GE).

Performance and Operational Requirements

A detailed performance and environmental specification is necessary in order to adequately interface with the generation or storage source and the utility grid. Generation sources will vary in voltage level. In addition the voltage range of operation will vary according to the generation source and the type of electrical storage if any. Advanced electrochemical storage systems should be clearly defined since a particular charge or discharge cycle may be excessive with respect to the capability of the power conditioner. Generally the power conditioners that have been described are adequately flexible in design so that they can be applied to an extensive range of

applications. These applications extend from photovoltaic systems, solar thermal systems, MHD systems, wind systems and load leveling systems.

Efficiency requirements are high in order to have low delivered energy costs. The UPS systems described previously typically have an inverter efficiency of 95% (600 VDC bus). The advanced technology inverters typically have efficiencies of 96% at full load and 92% at 25% load (14 MWe, 2200 VDC - 3800 VDC).

Utility line interface is another area which must be more clearly defined. These efforts for a more clearly specified direction will require the joint involvement of DOE, EPRI, Electric Utilities and Power Conditioner manufacturers. Some of the issues of line interference are addressed in EPRI Report 1024-1. Generally a 5% distortion of voltage or current is acceptable, but as a greater number of dispersed generation and storage units are interfaced with the utility grid, this value will likely be reduced toward 1% total harmonic distortion. Requirements at the Best Facility are 2% maximum harmonic injection.

Performance testing is an area of great importance since it is desirable to system or module test of the power conditioner prior to installation. Various methods for testing were discussed. These varied from calculation of losses for efficiency determinations to circulating module power back to back to supply only the module losses. Microprocessor control can aid in system testing and system trouble shooting. the microprocessor can be utilized as an important diagnostic tool.

Requirements to Stimulate Development

During the past several years important technical strides have been made in the development of advanced technology power conditioners. Two areas of support are suggested in order to arrive at optimum cost, efficiency and reliability goals. These areas are:

1. Additional development contracts to improve technology and componentry (see program recommendation and comments).
2. Placement of production contracts for large power conditioners to assist in optimizing cost, efficiency, reliability goals and delivered energy cost goals.

Technology Development Recommendations and Comments

During the workshop session various suggestions were made relating to both component and system technology and program direction. These suggestions have been summarized and are detailed as follows:

1. Develop system modeling of delivered energy cost versus component cost.

2. Provide better interface with various component vendors (battery, inverter) contractors and utilities to improve more adequate system engineering.
3. Analyze slow rate of batteries and other energy sources.
4. Review new technology batteries and power sources for unusual interface requirements.
5. Utilities to provide guidance for identification of permissible harmonic levels and utility characterization.
6. For forced commutation inverters the following technology areas would improve system cost, efficiency and protection.
 - A. Operation of inverter with a faulted bridge with higher harmonics.
 - B. Improved commutation capacitor technology.
 - C. Improved DC fusing technology.
 - D. Development of inverters with higher switching frequency for improved harmonic cancellation.
 - E. Advanced packaging and cooling methods.
 - F. Application of microprocessor technology to inverter and system control.
 - G. Improved power conditioner efficiency.
 - H. Snubber circuit technology improvement.
 - I. Improved SCR voltage, current and turnoff characteristics.
7. Allow market place to identify the most viable technology (line commutation versus forced commutation) from the standpoint of inverter cost, delivered energy cost, performance criteria.
8. For line commutated inverters the following should be investigated for improved cost, efficiency and ripple reduction and system protection.
 - A. Three inverter bank versus two bank systems for reduced harmonics.
 - B. Filter optimization for reduced harmonics.
 - C. Larger SCR's (100 mm cells).
 - D. Application of liquid cooling.

- E. Improvements in capacitors and use of synchronous capacitors.
 - F. Continued development of static DC interruptor with add-on microprocessor control.
9. Larger number of phases in line commutation inverter do not necessarily improve harmonic performance; therefore, development efforts may not provide performance improvements.
 10. Review static interrupter performance versus mechanical interrupter in terms of cost, protection and system performance.
 11. System electronic controls should be diagnostic in nature and remotely controllable for utility system power management.
 12. Factory testing of power conditioners should closely simulate the real installation environment. Procedures and methodology should be investigated.
 13. Study efforts should be extended in characterizing of system performance. A generalized system specification should be developed including electrical performance, environmental requirements, reliability, etc.
 14. Analysis of power conditioner modularity as related to cost reduction of installation costs.
 15. Analytical models are necessary for sources (PV, MHD, fuel cell, battery, etc.).
 16. More inverter units needed to be built to identify cost, reliability and performance issues.

Conclusion

The overall conclusion of this workshop was that a great deal needs to be done in the areas of power conditioner technology development, performance specifications and standards, harmonic injection and modeling of utility systems in order to more adequately predict operational performance. It is also recommended that additional funding be supplied to initiate power conditioner production in order to identify the system interactive problems and sensible cost goals. Production expertise is necessary to provide a viable system product.

APPENDIX F

GLOSSARY

This glossary contains a list of terms frequently used in discussion of electrochemical energy storage systems:

1. **Inverter:** A system whereby battery power is converted to AC power.
2. **Converter:** A system whereby AC power is converted to DC for battery charging.
3. **Silicon Controlled Rectifier (SCR):** A solid state static switch used in the inverter/converter modules.
4. **Line Commutated Inverter:** A type of inverter whereby SCR turnoff voltage is provided by the AC bus (natural commutation). Thus, the commutation process is accomplished automatically by the instantaneous relationship existing between the AC line voltages, and no additional circuit elements are required to provide stable commutation.
5. **Forced Commutation Inverter:** This term is applied to inverters which use an impulse artificially generated to briefly reverse the voltage on a conducting SCR. This impulse is generated by auxiliary means, separate from the main power circuit (or AC bus).
6. **Voltage Safety Factor:** It is the ratio between DC bus voltage and the nominal rating of the inverter thyristor. The DC bus voltage is defined as the maximum repetitive voltage, including repetitive external transients.
7. **Contactor:** An electrically actuated mechanical switch.
8. **Disconnect:** A switch used to mechanically disconnect an electrical circuit.
9. **Active Materials (Storage Battery):** The materials of the plates that react chemically to produce electric energy when the cell discharges and that are restored to their original composition in the charging mode of operation.
10. **Available:** A battery system is said to be available when there is a production facility that can produce it in large quantities (on the order of 1000 MWeh worth of batteries per year).
11. **Depth of Discharge (DOD):** The percentage of rated capacity that is removed during discharge. For example, the DOD of a cell rated at 100 AH is 80% when 80 AH is removed.

12. **Battery Energy Efficiency:** The ratio of energy removed from a fully charged battery (up to a specified DOD, under normal operating conditions) during discharge to the energy required to bring it again to full state of charge times 100%.
13. **Storage System:** It is comprised of the battery, power conditioning elements, protection units, and interface with utility bus (or common plant bus).
14. **Balance of System (BOS):** All components of the storage system less battery.
15. **Battery Capacity:** The energy, kWh, that the battery can deliver on discharge (to a specified DOD, under normal operating conditions) from the start to the end of its cycle life.
16. **Levelized Energy Cost:** That price per unit of energy which, if held constant throughout the life of the system would provide the required revenue, assuming that all cash flow interim requirements or excesses are borrowed or invested at the utility's internal rate of return.